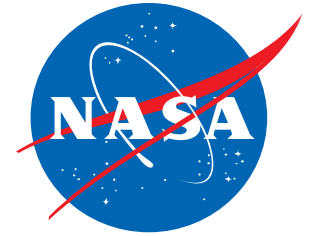




National Aeronautics and Space Administration



# Overview of Spaceflight Effects on Humans and Guided Discussion of Collaboration Ideas

NASA Human Research Program  
Hosting Orientation Visit for Santa Fe Institute  
22 September 2014

**Mark Shelhamer, Sc.D.**  
**Chief Scientist**  
**[mark.j.shelhamer@nasa.gov](mailto:mark.j.shelhamer@nasa.gov)**



# The Big Picture

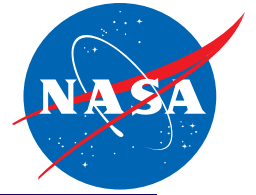
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- Need to better understand human adaptation to space
    - ✓ Provide better countermeasures
      - Integrated approaches to minimize resources
    - ✓ Provide tools for autonomy
    - ✓ Assess and maintain resilience
      - Individual
      - Team
  
  - Advantages
    - ✓ Relatively homogeneous, motivated, well-characterized subjects.
    - ✓ Well-defined and characterized environment.
    - ✓ Subject compliance rarely an issue.
  
  - Disadvantages
    - ✓ Small population
    - ✓ Not analogous to terrestrial populations on Earth
-

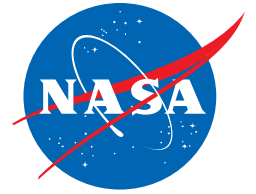


# Outline



*Human Research Program*

1. Spaceflight environment and effects on the human
  - Need for integrated conceptual approach
2. Human response to space flight
  - Behavioral health
  - Physiological health
  - Radiation-induced health responses
3. Interaction of the human with spacecraft and operations
  - Clinical physical health support from medical system
  - Physical and cognitive performance support from system interfaces
4. Areas of convergence and integration
5. Approaches to integration and modeling
  - Reference / backup

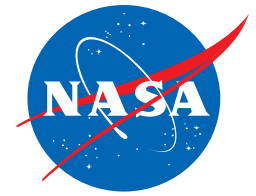


*Human Research Program*

# **1. Problem Introduction:**

## **The Spaceflight Environment and Effects on the Human**





Human Research Program

# HUMAN EXPLORATION

NASA's Path to Mars



## EARTH RELIANT

MISSION: 6 TO 12 MONTHS  
RETURN TO EARTH: HOURS



Mastering fundamentals  
aboard the International  
Space Station

U.S. companies  
provide access to  
low-Earth orbit

[www.nasa.gov](http://www.nasa.gov)

## PROVING GROUND

MISSION: 1 TO 12 MONTHS  
RETURN TO EARTH: DAYS

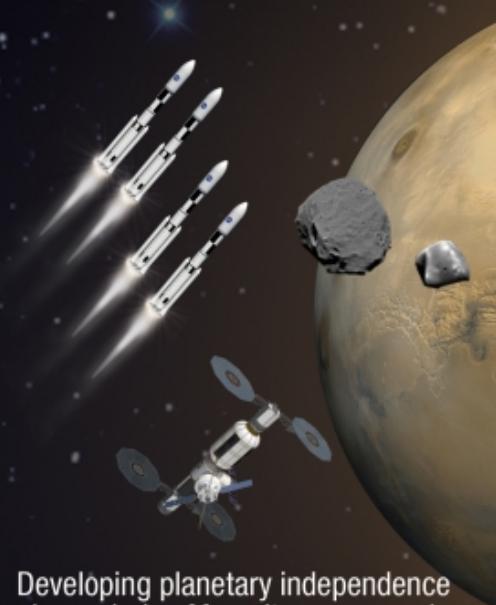


Expanding capabilities by  
visiting an asteroid redirected  
to a lunar distant retrograde orbit

The next step: traveling beyond low-Earth  
orbit with the Space Launch System  
rocket and Orion spacecraft

## MARS READY

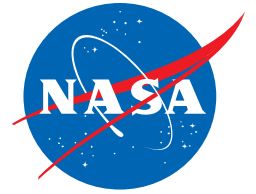
MISSION: 2 TO 3 YEARS  
RETURN TO EARTH: MONTHS



Developing planetary independence  
by exploring Mars, its moons and  
other deep space destinations



# Primary Hazards to Humans during Space Flight



Human Research Program

- **Decreased gravity**

(including gravity transitions & launch/landing loads)

*bone, muscle, cardiovascular, sensorimotor, nutrition, immunology  
behavior/performance, human factors, clinical medicine*

- **Isolation/confinement/altered light-dark cycles**

*behavior/performance*

- **Hostile/closed environment**

(including habitability: atmosphere, microbes, dust,  
volume/configuration, displays/controls)

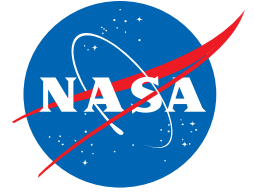
*behavior/performance, nutrition, immunology, toxicology,  
microbiology*

- **Increased radiation**

*immunology, carcinogenesis, behavior/performance, tissue  
degeneration, pharmaceutical stability*

- **Distance from Earth**

*behavior/performance, autonomy, food systems, clinical medicine*



# Space Flight Affects Humans

Human Research Program

- Affects most systems of the body
  - Sensorimotor, Cardiovascular, Muscle, Bone, Immune
- Different time courses and magnitudes
- Consequences for health *and* performance (physical *and* behavioral)
- Responses commonly explored individually
- Systems interact in ways we do not yet understand
- Adaptation to “space normal” occurs

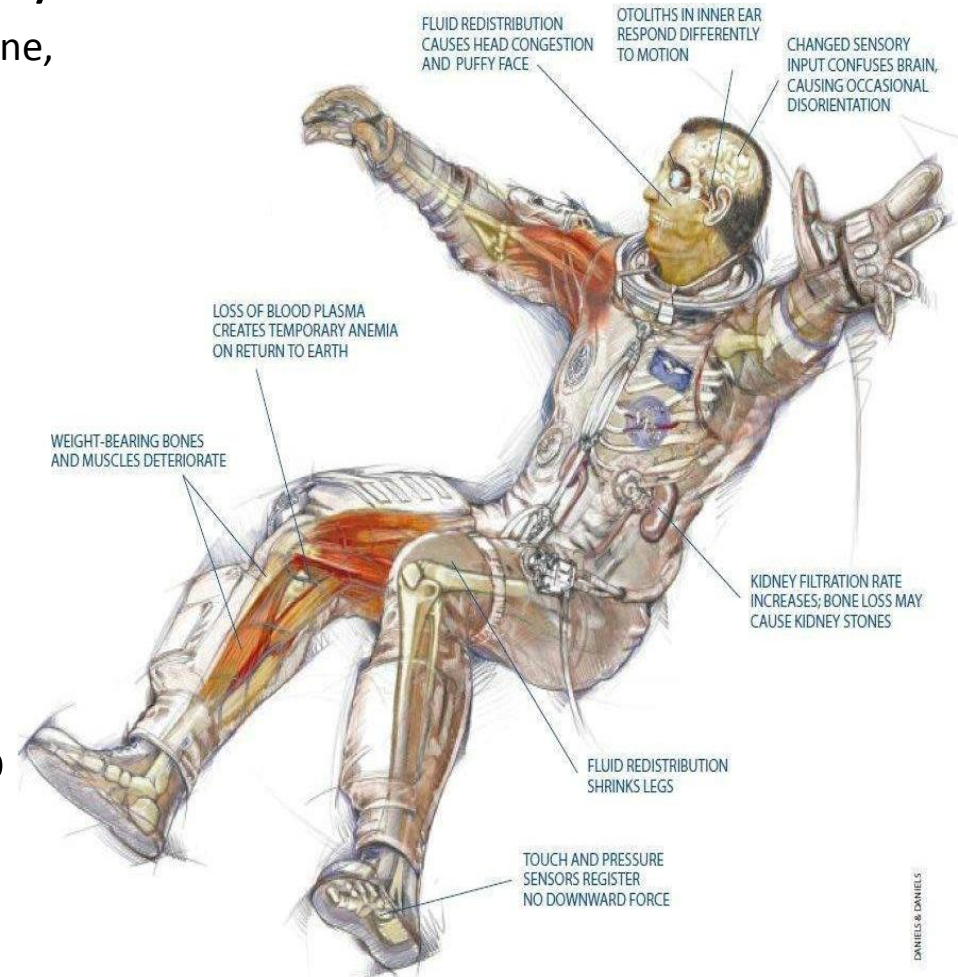
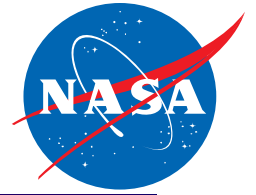


Image from: <http://zerog2002.de/bodyreactions.html>

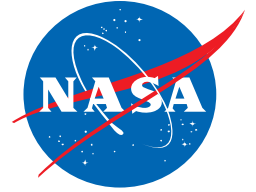


# Potential Collaboration



Human Research Program

- The intention behind this potential working group is to:
  - 1) Explore both the challenges and analysis techniques for working with high-dimensional datasets spanning behavior, physiology, and human-machine interactions, and
  - 2) Consider the interacting complex systems of long-term space flight.
- **Need *integrated* understanding of how organism as a whole responds to spaceflight**

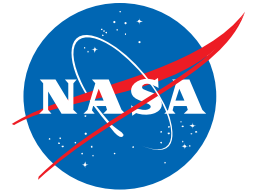


*Human Research Program*

## **2. Human Response to Spaceflight**

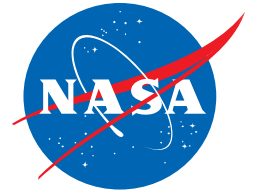


# What to Expect Next



*Human Research Program*

- For each of the major HRP areas:
  - Effects due to spaceflight
  - Risks for future spaceflight missions
  - Countermeasures
  - Current modeling efforts
  - Descriptions of typical data in that area of study



*Human Research Program*

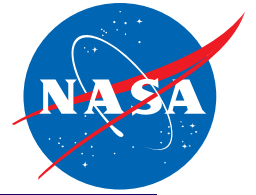
# Human Response to Spaceflight: Behavioral Health

**HRP's Behavioral Health and Performance (BHP) Element**





# Behavioral Health



*Human Research Program*

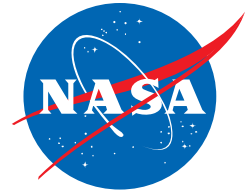
- Behavioral areas susceptible to increased risk over a one-year mission:
  - (1) sleep loss, circadian desynchrony, workload and fatigue
  - (2) stress, morale and mood changes\*
  - (3) cognitive functioning
  - (4) interpersonal conflicts\*
  - (5) motivational challenges\*
  - (6) family separation and personal communications
  
- Preliminary analysis for ISS (ongoing study):
  - Available measures of subjective stress, sleep quality, and vigilance
    - ✓ not all monotonic with mission time
    - ✓ do not plateau by six months
  - Sleep quality and vigilance have similar trends, which suggests increasing performance deficits for longer missions.
  - There are correlations between stress, sleep, tiredness, and physical exhaustion that suggest an underlying physiological factor.

Even if stress is compensated and does not affect performance, it may produce adverse physiological changes (immune function).





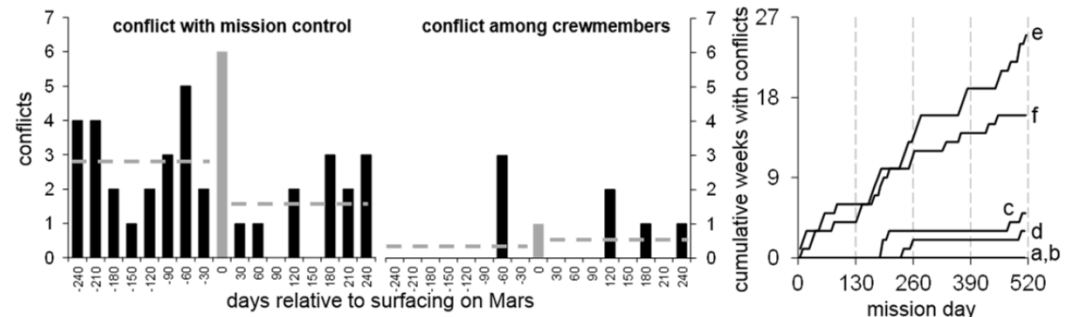
# Behavioral Health in Spaceflight Analogs



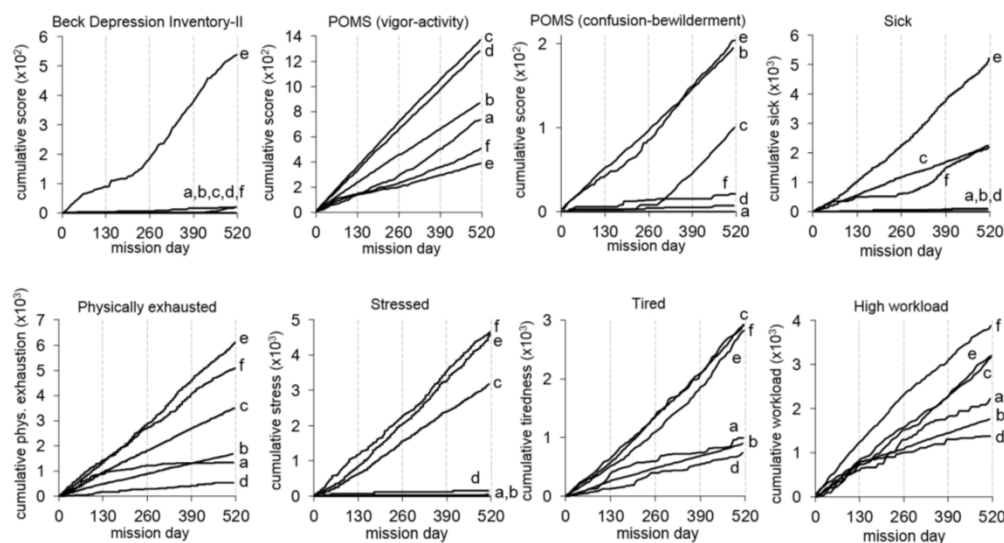
Human Research Program

## ***Psychological and Behavioral Changes during Confinement in a 520-Day Simulated Interplanetary Mission to Mars (Basner et al., 2014)***

- Depressive symptoms (n=1)
- Increased stress (n=3)
- Elevated levels of confusion and bewilderment (n=3)
- Elevated conflict (n=2)



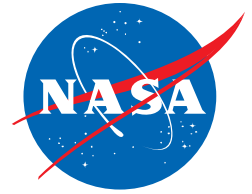
Onset of symptomology usually occurred in the first quarter, but some symptoms showed up later (i.e., confusion-bewilderment in subject c).





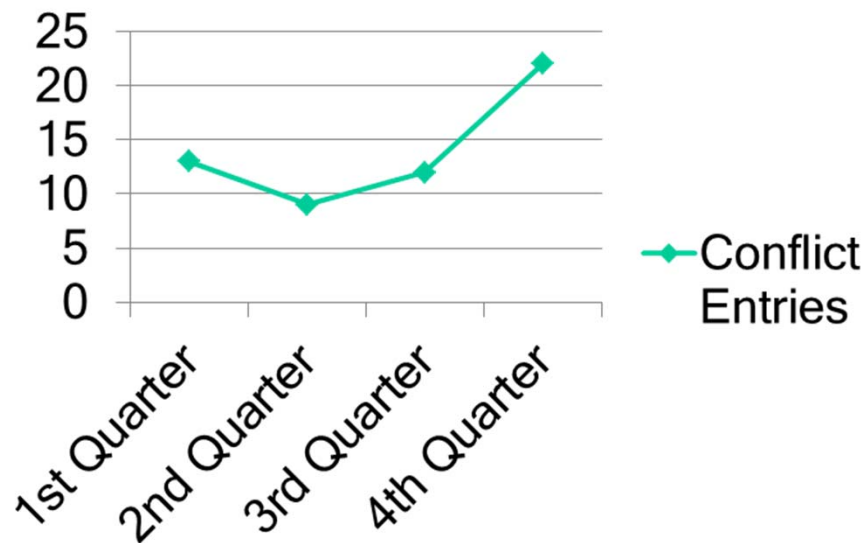
# Behavioral Concerns for One-Year ISS Missions

## Interpersonal Conflicts

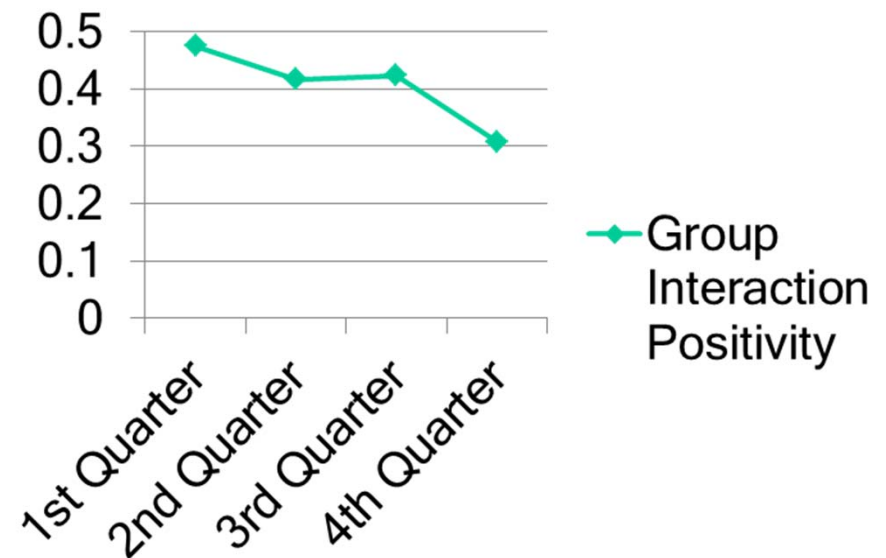


Human Research Program

- ISS Journal entries on conflict by mission quarter



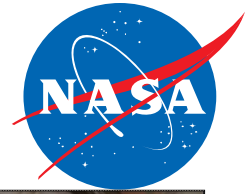
- ISS Group Interaction Positivity Ratings by mission quarter (244 entries)



Interpersonal conflict can impact crew performance and mission success (De Dreu & Weingart, 2003)

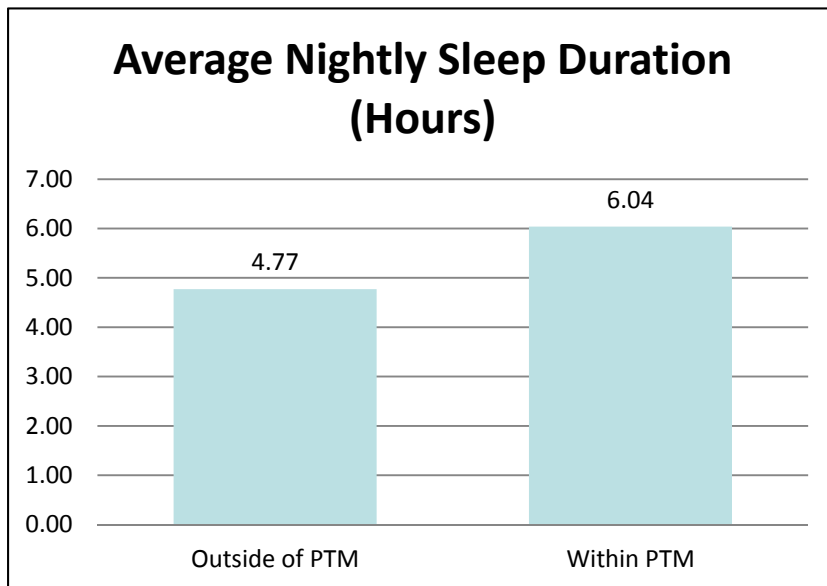


# Sleep in Space



## ***Sleep-Wake Actigraphy and Light Exposure During Spaceflight – “Sleep-Wake” (Czeisler, Barger, et al., 2012)***

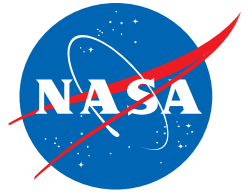
***In addition to sleep loss, circadian desynchrony seems to occur on ISS.*** Estimates of circadian phase were generated by the validated model in the Circadian Performance Simulation Software.



- Sleep deficiency on ISS missions was similar to Shuttle missions (~ 6 hours)
- Based on Shuttle data, there is no significant difference in average nightly sleep duration when taking medications (6 hours) versus when not taking medications (5.82 hours)



# Risks for Future Space Flight Missions



*Human Research Program*

## Current Operations

### Low-Earth Orbit

- Real-time communication with ground operations
- Real-time com with family and friends
- Provision of crew care packages
- Evacuation options

Large Volume and Private Quarters

Six-Month Duration (to date)



## Exploration Class Missions

### Major Issues

- Selection and Crew Composition
- Psychosocial Adaptation & Training
- Growth and Resiliency
- Sleep, Fatigue, Workload & Circadian
- Net Habitable Volume
- Family Communication and Support

### Emerging Issues

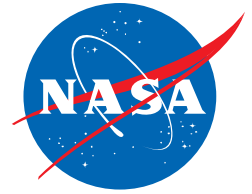
- Risk Characterization
- Stress, Conflict
- Family Separation







# Behavioral Health and Performance - Example Countermeasures and Models in Development

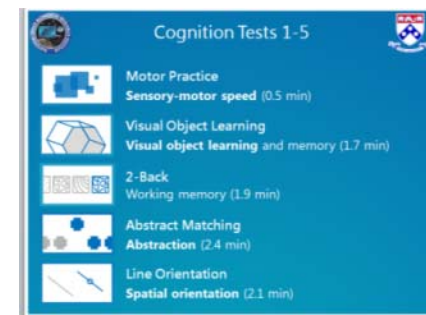


## Human Research Program

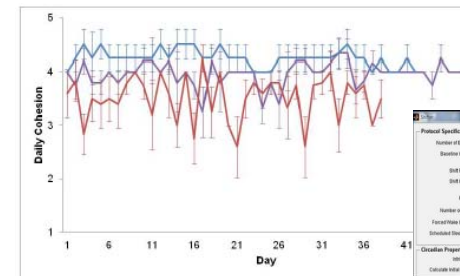
- Behavioral Health
  - Stress Management and Resilience Training for Optimal Performance (SMART-OP) (PI: Rose) –multimedia program for stress management
  - Cognition (formerly NeuroCATs) (PI: Basner) - cognitive test battery for real-time evaluation of astronauts in space
- Team
  - Team Dimensional Training (PI: Smith-Jentsch) - new team debriefing strategy for use by flight directors in mission control
  - Just in Time Training Development (PI: Ramachandran) software training platform for just-in-time teamwork skills training
  - Sociometric Badge Study (PI: Kozlowski) - Validation of sociometric badge developed for monitoring team functioning
- Sleep
  - Scheduling tools to support mission planning
  - Software to predict performance based on sleep-wake data
    - Circadian Neurobehavioral Performance and Alertness (PI: Klerman)
    - Individualized Fatigue Meter in BHP-DS (PI: Mollicone)
  - Individualized countermeasure regimen (e.g. light, darkness, melatonin, diet, exercise, medications)



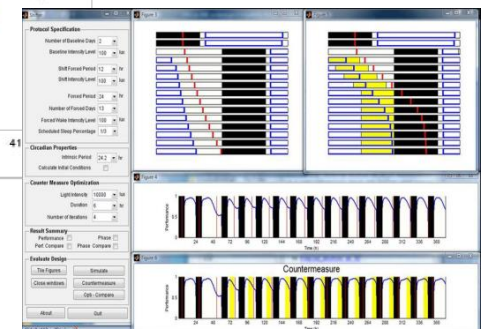
SMART-OP  
Screenshots of  
Focused Breathing,  
Effective  
Communication and  
Compartmentalization  
modules



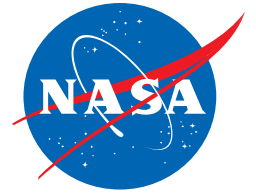
Portion of  
Cognition test  
battery



Team cohesion support



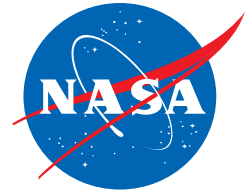
Sleep and planning support



*Human Research Program*

# Human Response to Spaceflight: Physiological Health

**HRP's Human Health and Countermeasures (HHC) Element**



# Human Health and Countermeasures Risks

## **Short-Term Health**

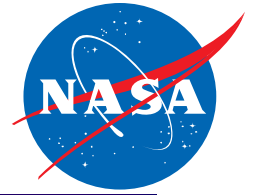
1. Risk Factor of Inadequate Nutrition
2. Risk of Bone Fracture
3. Risk of Cardiovascular Disease
4. Risk of Injury and Compromised Performance due to EVA Operations
5. Risk of Injury From Dynamic Loads
6. Risk of Decompression Sickness
7. Risk of Crew Adverse Health Event due to Altered Immune Response
8. Risk of Intervertebral Disc Damage
9. Risk of Renal Stone Formation
10. Concern of Clinically Relevant Unpredicted Effects of Medication

## **Mission Performance**

11. Risk of Impaired Control of Spacecraft, Associated Systems, and Immediate Vehicle Egress Due to Vestibular/Sensorimotor Alterations Associated with Spaceflight
12. Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance
13. Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity
14. Risk of Orthostatic Intolerance During Re-Exposure to Gravity

## **Long-Term Health**

15. Risk of Early Onset Osteoporosis Due to Spaceflight
16. Risk of Spaceflight-Induced Intracranial Hypertension/Vision Alterations

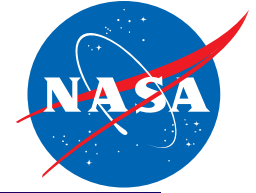


# Muscle

*Human Research Program*

- Muscle unloading → muscle atrophy
- Muscle structural and metabolic alterations
- Countermeasures: exercise and pharmaceutical
  - Studies show effectiveness of largely maintaining muscular capability.
- Residual divergence from earth-normal capabilities is still hypothesized for mission durations from 6-12 months.
  - not all muscles, for example postural muscles, are engaged to the same degree in-flight as on the ground, and long-term disuse will continue to contribute to degradation of some muscle groups.
- Despite this, majority of the crew is expected to meet the standards currently defined for muscle strength
- However considerable variability among crew exists and some do not meet the NASA standard

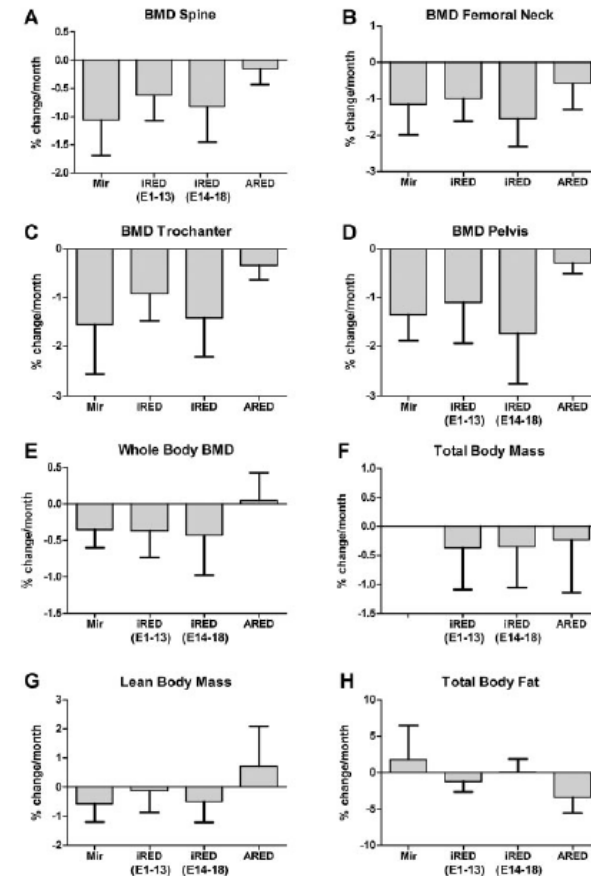




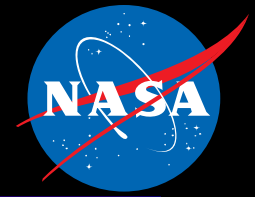
# Musculoskeletal

## Human Research Program

- Unloading →
  - Bone loss → increased risk of renal stone
  - Muscle loss (strength/power/endurance)
  - Spinal elongation
    - Seated height can increase up to 6%
- Bone loss countermeasures
  - Resistive exercise plus bisphosphonates
    - very effective to date
- Muscle atrophy countermeasures
  - Aerobic and resistive training
  - Highly variable response
    - 60-80% contributed by genetics
    - Non-response in some astronauts



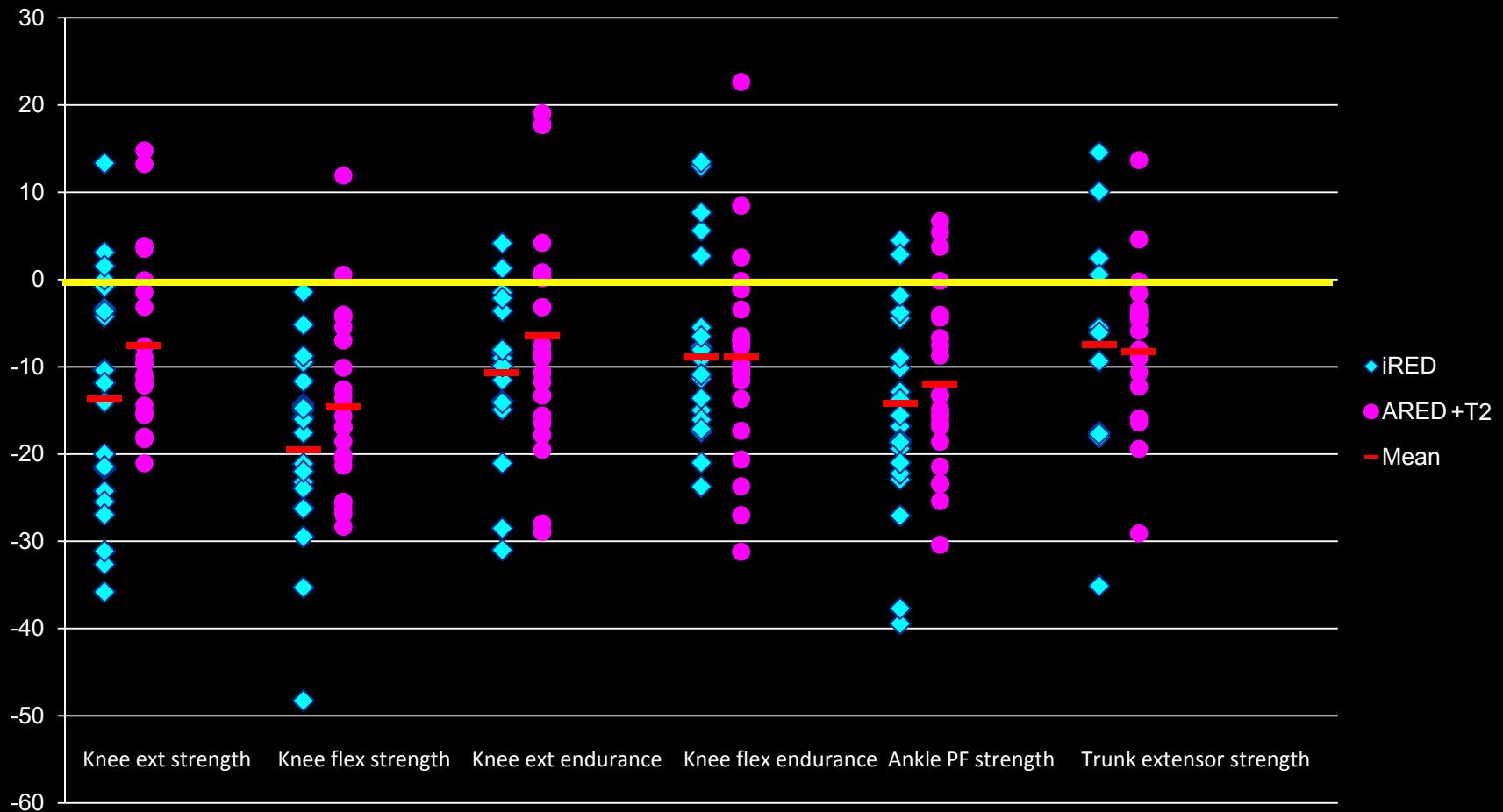
Osteoporosis International  
(2012): 1-10.



# Muscle Function

Exp 1-32 (IRED n=22 ARED+T2 n=25)

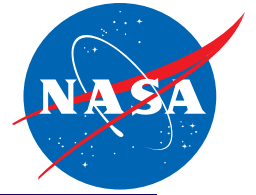
Human Research Program



Ploutz-Snyder et al. 2014



# Bone

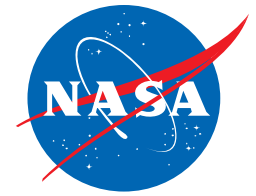


*Human Research Program*

- Mechanical unloading of skeletal system → bone loss
- Other potential contributing factors: altered nutritional and endocrine system states
- Biochemical markers of bone turnover suggest unbalanced increase in bone resorption by two weeks into flight (Smith 2005)  
→ may lead to a net loss in bone (Orwoll 2013)
- Countermeasures: exercise and pharmaceutical
  - Studies show reduction in decrement of bone loss in terms of bone mineral density (Leblanc 2013; Smith 2012; Sibonga 2013)
- Plateau could be attained for some individual astronauts on a 6-month mission (LeBlanc 2013 and Sibonga 2013 )



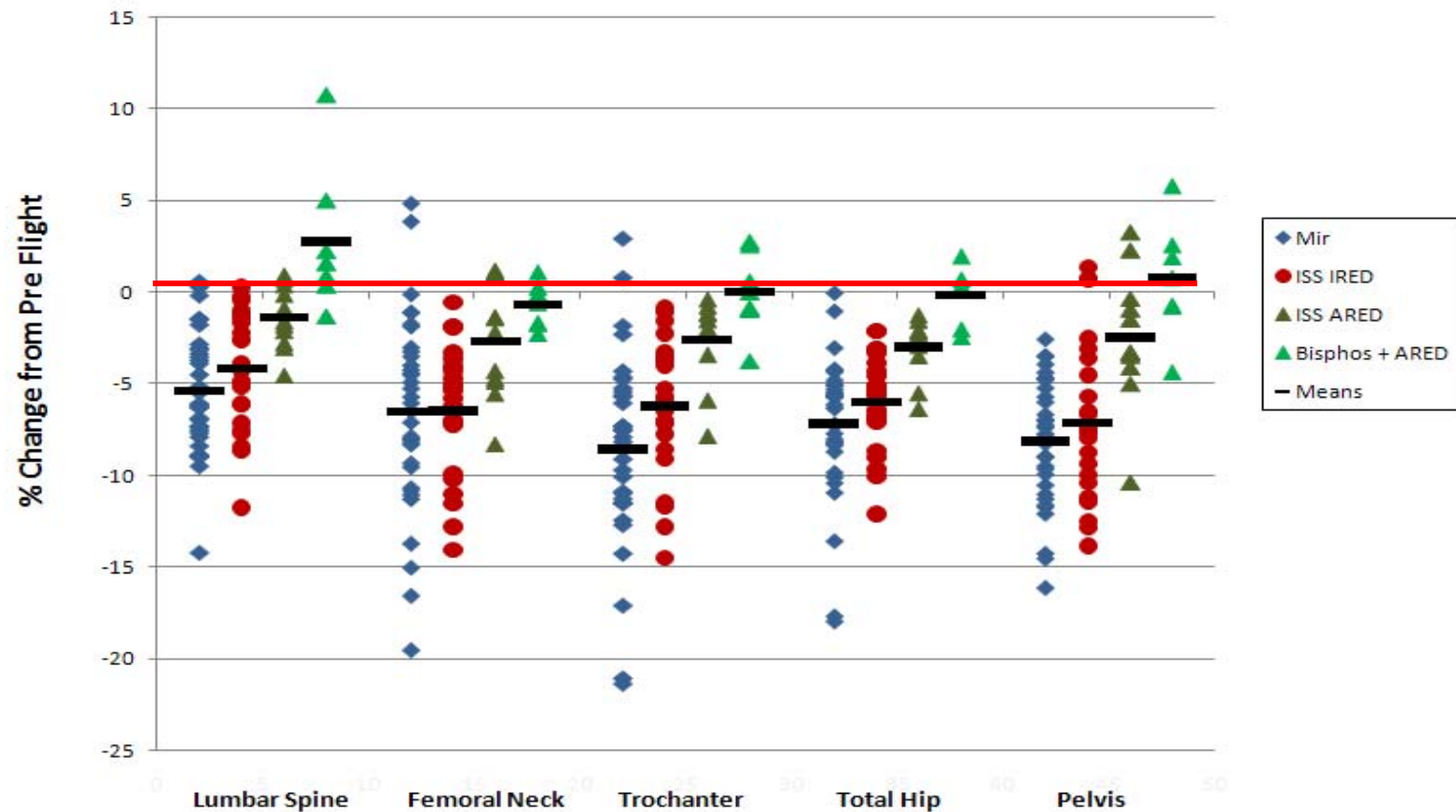
# Bone



Human Research Program

## % Change in DXA BMD after Long-Duration Mir and ISS Missions

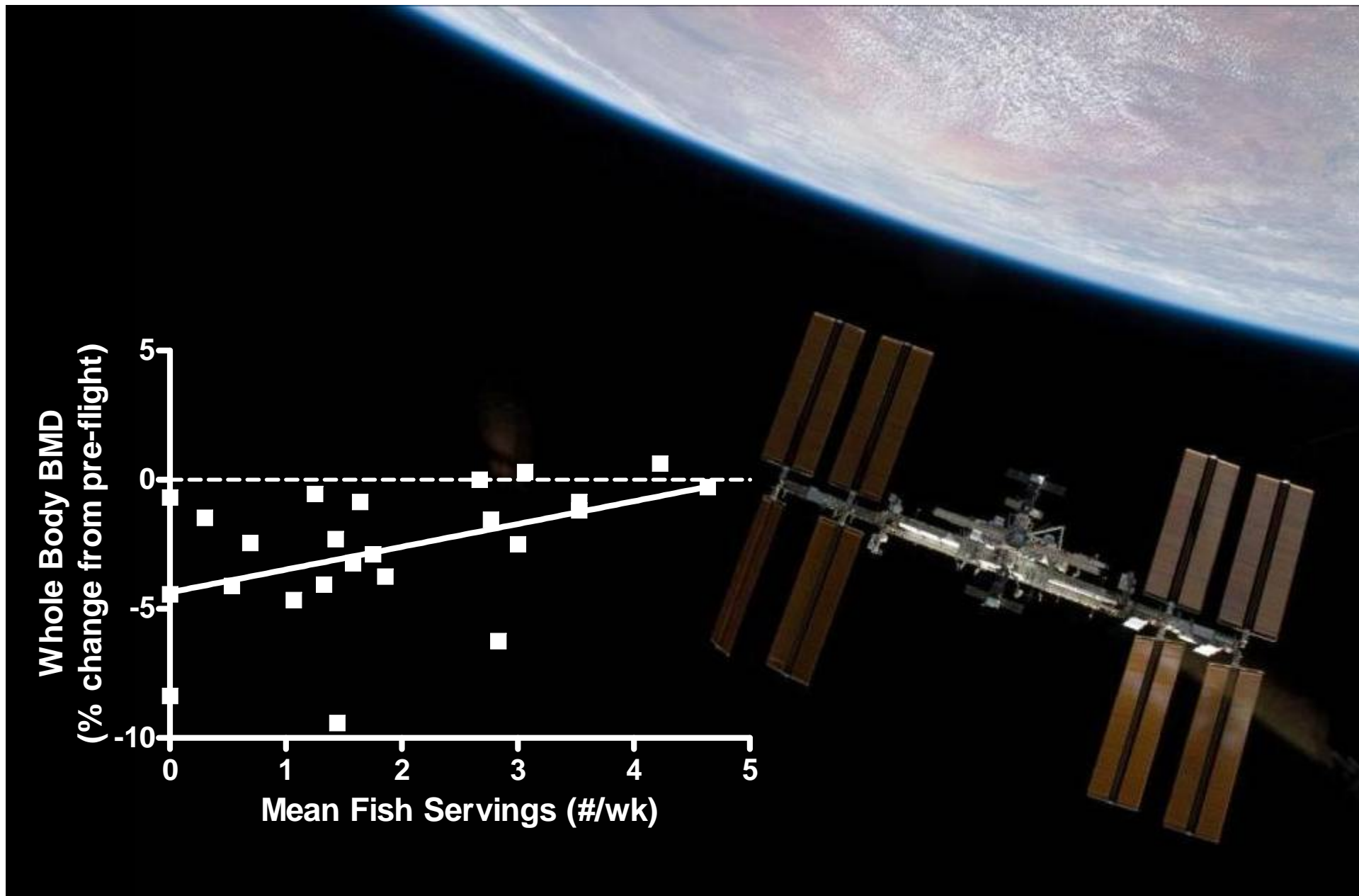
Mir n=35; ISS IRED n=24; ISS ARED n=11; Bisphos + ARED n=7



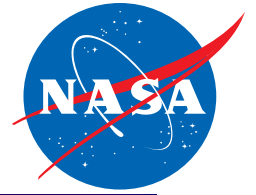
1217

\* Updated data since 2010 Bone Summit

Sibonga et al. 2014



Smith et al. 2010



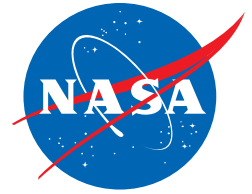
# Sensorimotor

Human Research Program

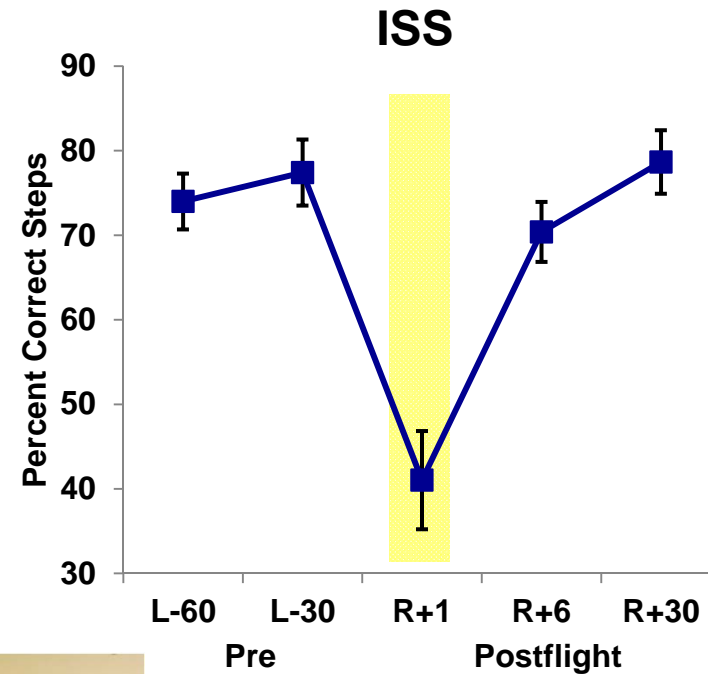
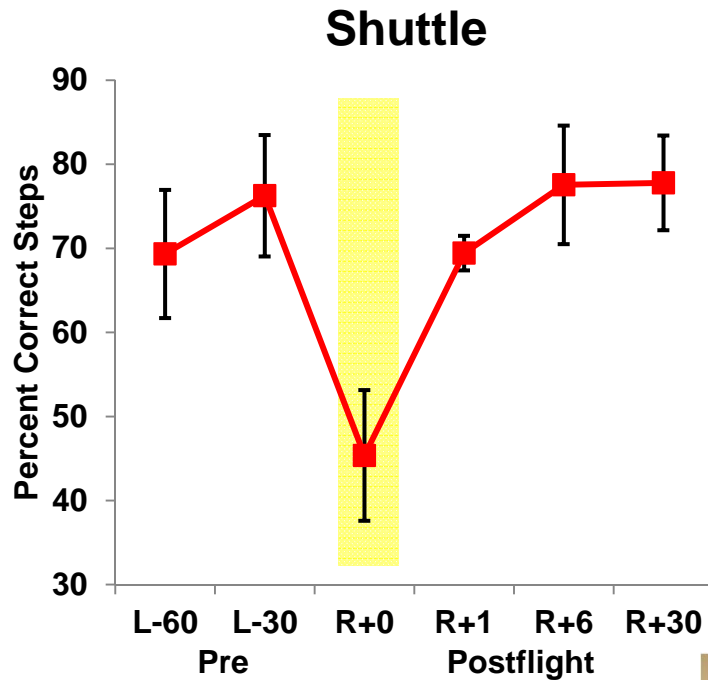
- Gravity provides static orientation and dynamic movement information terrestrially, its removal in spaceflight → altered:
  - Eye-head-hand control, postural and/or locomotor ability, gaze function, and perception (Clement and Reschke, 2008)
- After gravitational transitions, the sensorimotor control system adapts to altered sensor inputs (without gravity)
  - Initial adaptation spike, dynamic changes in early days and weeks
  - Then slower, more stable adaptation diverging from earth-normal but still within the current acceptable standard limits.
- Countermeasures: none currently in-flight; post-flight through operations
- After return to Earth's gravity from a 6-month mission, large changes are seen in the sensorimotor system's performance due to altered central integration of sensory input (Mulavara et al. 2010; Wood et al. 2011)
  - Recovery of pre-flight capabilities is seen relatively quickly, within approximately a month



# Tandem Walk Test



Human Research Program



## Incorrect Steps:

sidestepped, opened eyes,  
or paused for more than  
three seconds between steps

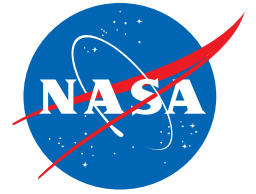


Bloomberg et al. 2014





# Field Test



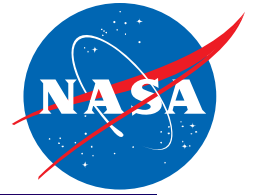
Human Research Program



## Objectives:

- 1) Characterize the functional decrements immediately after landing.
- 2) Construct a recovery timeline of crewmember functional performance starting within hours of landing through the return to normative preflight levels.
- 3) Compare the efficacy of U.S. Gradient Compression Garment (GCG) to the Russian Kentavr suit for control of orthostatic intolerance.



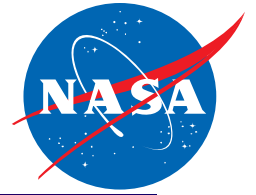


# Cardiovascular

*Human Research Program*

- Shift of fluids toward head and deconditioning → aerobic capacity shows fairly steep decline during first few weeks of a mission
- Countermeasures: aerobic exercise on orbit
- Data have indicated a stabilization of aerobic capacity during the first couple months of a mission, on average
  - However, individual variability shows complete preservation in some cases and larger decline in others
- Atherosclerosis and vascular dysfunction expected to be a consequences of the spaceflight environment
  - e.g. exposure to radiation, oxidative and mental stress, possible lifestyle (exercise and nutrition) alterations
- However, this is one of the areas with the least data available currently (preliminary data from internal (LSAH) data mining study, conference proceeding at ISGP 2014 Waterloo)
- Hypothesized that inflight changes will be well above that expected in a normal population





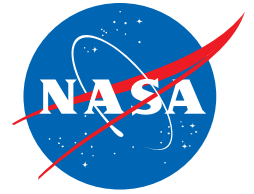
# Immune

*Human Research Program*

- Adaptation issues and physiological stress → immune dysregulation in early phase of flight such as:
  - Altered peripheral leukocyte distribution
  - Altered T cell function and changes in cytokine profiles (both plasma and mitogen stimulated)
  - Latent herpesvirus reactivation (Crucian et al. 2012; Mehta et al. 2000; Mehta et al. 2014, Pierson et al. 2005)
- Most dynamic changes during the first few weeks of flight
- Immune dysregulation continues in mission
  - Based on characterization of immune parameters (Crucian et al. 2013, Mehta et al. 2013)
  - Also recent incidence survey identified in-flight incidence of contact hypersensitivities, high on-orbit use of topical steroids, persistent allergic symptoms responsive to antihistamines (Crucian et al. 2014)
- Countermeasures: no preventive ones at this time
  - Possibilities: nutritional supplementation and vaccine options
  - Other general countermeasures such as exercise, improved work schedules, stress management and radiation shielding may also somewhat benefit the immune decrement

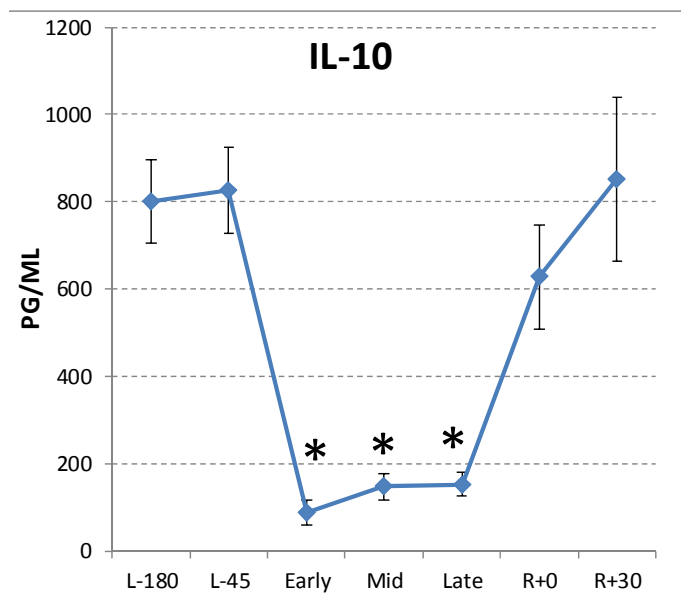


# Immunity is Altered During Long-duration Spaceflight onboard ISS



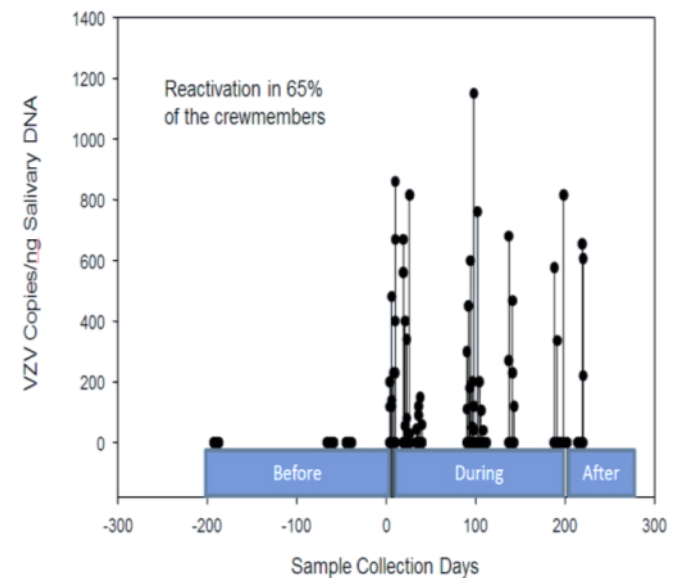
Human Research Program

## Cytokine Production Profiles



N = 22

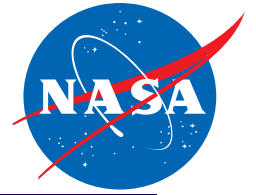
## Latent Herpesvirus Reactivation



Crucian et al. 2014



# Translational Research

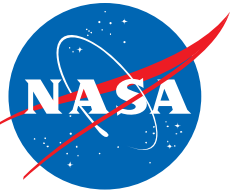


*Human Research Program*

- Spaceflight may cause changes to the human at many levels, from DNA to physiological and neurobehavioral



# Differential Effects on Homozygous Twin Astronauts Associated with Differences in Exposure to Spaceflight Factors

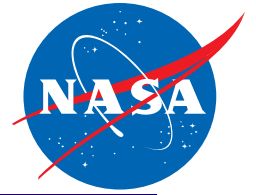


*Human Research Program*

- Statement of problem:

“There is a singular opportunity to propose limited, short-term investigations examining the differences in genetic, proteomic, metabolomics, and related functions in twin male monozygous astronauts associated with differential exposure to spaceflight conditions. This opportunity has emerged from NASA’s decision to fly veteran NASA astronaut Scott Kelly aboard the International Space Station (ISS) for a period of one year commencing in March 2015, while his identical twin brother, retired NASA astronaut Mark Kelly, remains on Earth.”

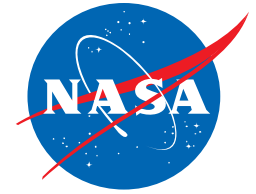
NNJ13ZSA002N-TWINS Appendix D



# Twins Pilot Specific Aims

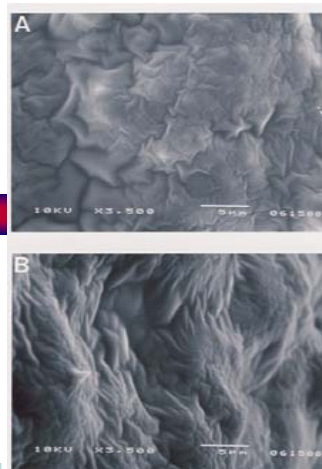
*Human Research Program*

- Conduct a pilot demonstration project focused on the use of integrated human -omic analyses to better understand the biomolecular responses to the physical, physiological, and environmental stressors associated with spaceflight.
  1. Genome
  2. Epigenome
  3. Transcriptome
  4. Proteome
  5. Metabolome
  6. Microbiome
  7. Physiology
  8. Neurobehavioral



**Neural Progenitor  
Cells Repeatedly  
Subjected to the  
Suborbital  
Environment**

**Examined for  
Cumulative Effects on  
Gene Regulatory and  
Metabolic Networks**



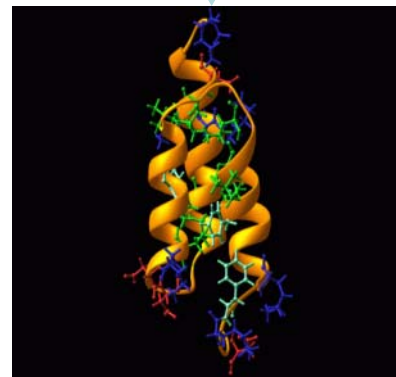
**Genome**

**20-25,000  
human genes**



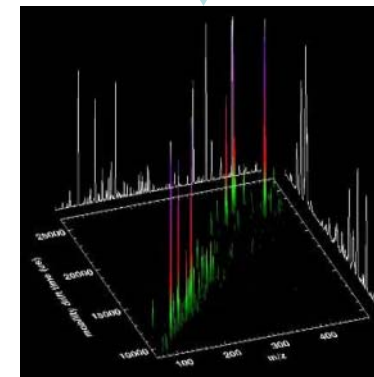
**Transcriptome**

**100,000 mRNAs**



**Proteome**

**1M Proteins**



**Metabolome**

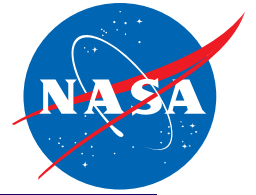
**5,000-10,000  
metabolites**

Schmidt, MA, Goodwin, TJ copyright  
©2012





# Visual Impairment and Intracranial Pressure (VIIP)



*Human Research Program*

- Subset of crewmembers experience visual performance decrements
  - cotton-wool spot formation
  - choroidal fold development
  - optic-disc edema
  - optic nerve sheath distention
  - and/or posterior globe flattening
  - with varying degrees of severity and permanence.
- Changes potentially caused by events precipitated by fluid shift toward head in spaceflight
- Some crewmembers possibly more susceptible to these changes due to genetic/anatomical predisposition or lifestyle (fitness) factors

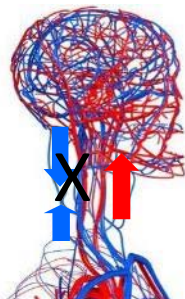
(NASA HRP Evidence Report: Risk of Spaceflight-Induced Intracranial Hypertension and Vision Alterations, Version 1.0, July 12, 2012)



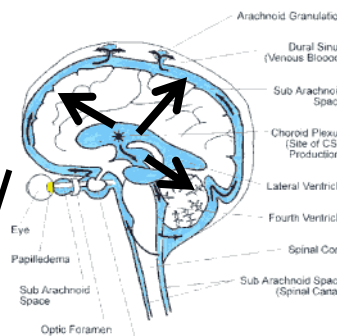
# VIIP Pathophysiology



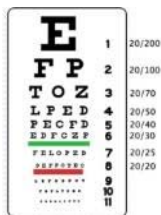
## 1. Headward fluid shift due to microgravity



## 2. Fluid shift causes increased intracranial pressure (ICP)



## 3. Elevated ICP transmitted to the eye and optic nerve

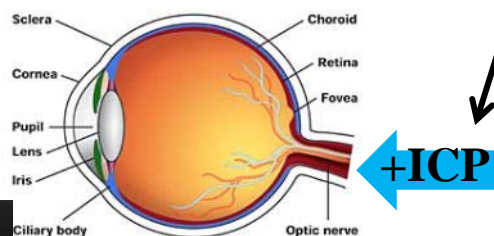
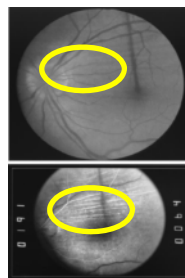


•**Hyperopic Shifts**  
Up to +1.75 diopters

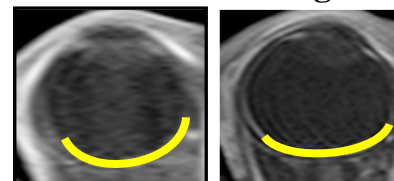
•**Choroidal Folds**  
Parallel grooves posterior pole

•**Altered Blood Flow**  
“Cotton wool” spots

•**Scotoma**  
Abnormal Visual Field



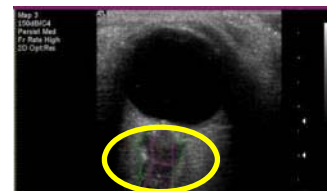
•**Globe Flattening**



Normal Globe

Flat Globe

•**Increased Optic Nerve Sheath Diameter**



•**Optic Disc Edema (swelling)**





# Current U.S. ISS VIIP Incidence

---



41 U.S. ISS astronauts flown to date as of Expedition 32:

- *Unclassified astronauts N=16* (No MRI, OCT or ocular US)
- Non-cases N=6
- **Confirmed cases: 19**

---

## Clinical Classification:

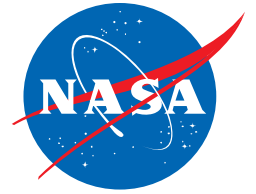
- |                   |   |                  |                               |
|-------------------|---|------------------|-------------------------------|
| - Class One N=2   | } | 68.4 % Class 1&2 | } Increasing<br>severity<br>↓ |
| - Class Two N=11  |   |                  |                               |
| - Class Three N=2 | } | 31.6 % Class 3&4 |                               |
| - Class Four N=4  |   |                  |                               |

**Current VIIP Incidence as a % of U.S. ISS astronauts tested= 76.0%**

---



# CO<sub>2</sub> Exposure



*Human Research Program*

- Example of interaction of the human with the spacecraft environment → health effects due to CO<sub>2</sub> exposure



# Current CO<sub>2</sub> Status

## State of Knowledge (New Evidence)

---

### Ground-based Evidence

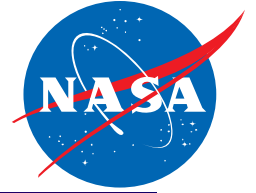
#### Is CO<sub>2</sub> an Indoor Pollutant? Direct Effects of Low-to-Moderate CO<sub>2</sub> Concentrations on Human Decision-Making Performance

*Usha Satish,<sup>1</sup> Mark J. Mendell,<sup>2</sup> Krishnamurthy Shekhar,<sup>1</sup> Toshifumi Hotchi,<sup>2</sup> Douglas Sullivan,<sup>2</sup> Siegfried Streufert,<sup>1</sup> and William J. Fisk<sup>2</sup>*

<sup>1</sup>Department of Psychiatry and Behavioral Science, Upstate Medical University, State University of New York, Syracuse, New York, USA;  
<sup>2</sup>Indoor Environment Department, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Environmental Health Perspectives • VOLUME 120 | NUMBER 12 | December 2012

- Decision-making performance (n=22) reaches dysfunctional levels for several measures during 2 ½-hour exposures to CO<sub>2</sub> at 1.9 mmHg
  - Visual effects reported (n=3) after ~30 min at 19 mmHg CO<sub>2</sub>: decreased depth perception (Sun et al., 1996), motion detection (Yang et al., 1997)
  - Risk of headache increases with increasing 24-hr average levels of CO<sub>2</sub> in the range of 2-5 mmHg aboard ISS
  - Occurrence of numerous “*space viscosity*” events aboard ISS
  - Increased cerebral blood flow at high CO<sub>2</sub>
  - ISS level: 3 mmHg mean, >5 mmHg peak (normal atmosphere: 0.30 mmHg)
-

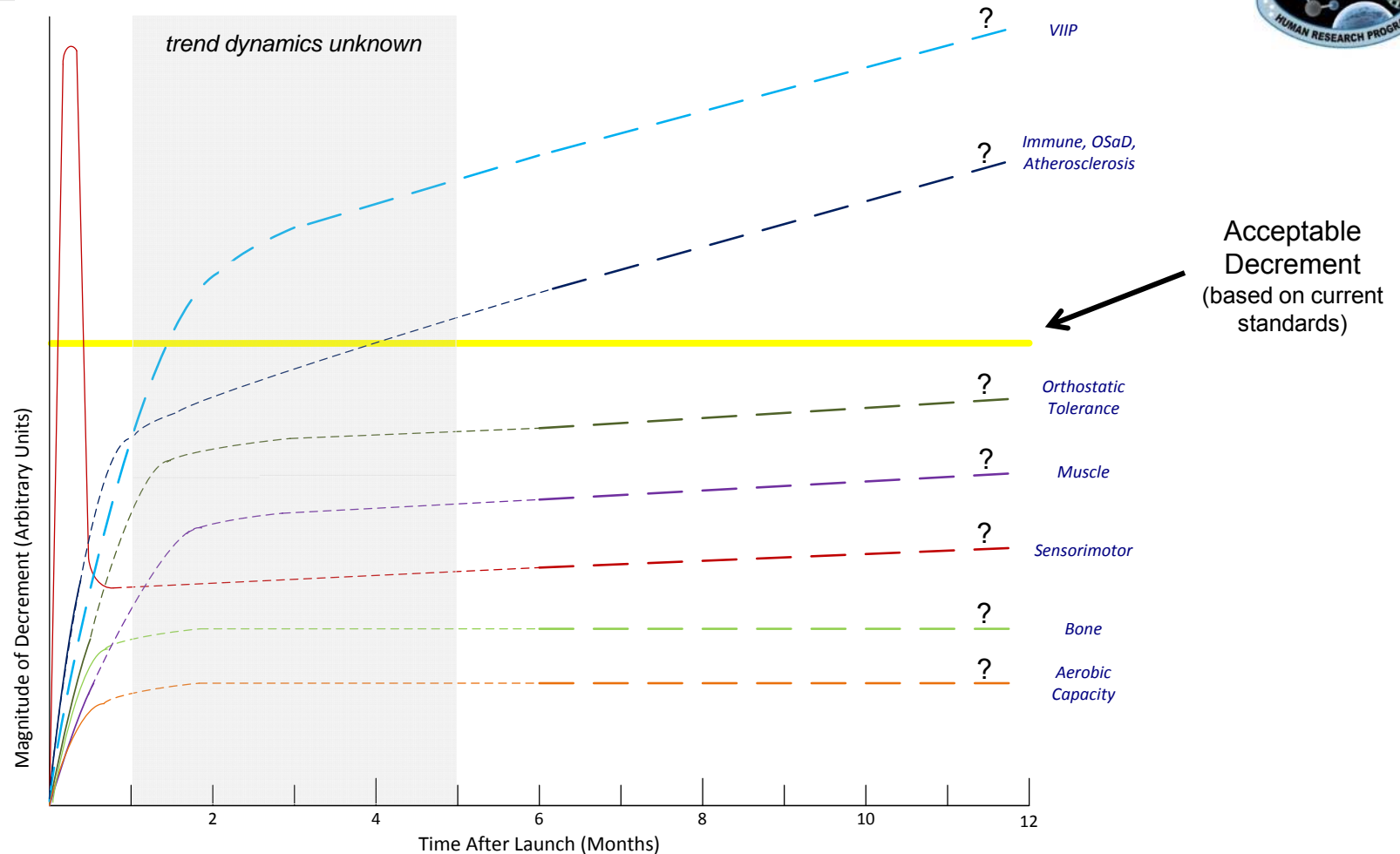


*Human Research Program*

# Notional Physiological Summary

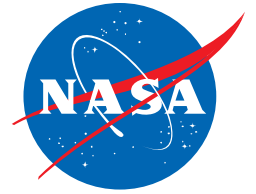


# In-Flight Physiological Changes



- Notional qualitative view of changes assuming currently known and **effective countermeasures** used
- Increased dash size = increased uncertainty in trend
- Individual variability not shown

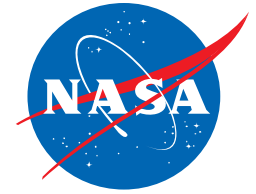




*Human Research Program*

# Human Response to Spaceflight: Radiation-induced health responses

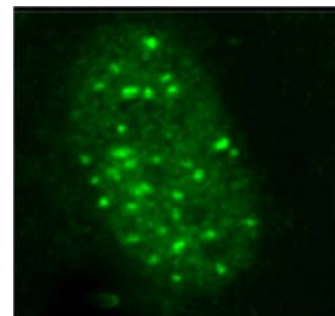
## **HRP's Space Radiation (SR) Element**



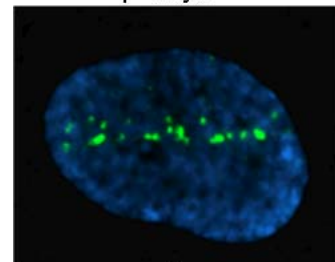
# The Space Radiation Problem

Human Research Program

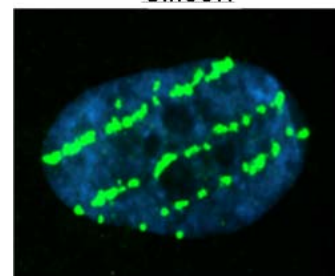
- Space radiation is comprised of high-energy protons and heavy ions (HZE's) and secondary protons, neutrons, and fragments produced in shielding and tissue
- Unique damage to biomolecules, cells, and tissues occurs from HZE ions that is qualitatively distinct from X-rays and gamma-rays on Earth
- No human data to estimate risk from heavy ions
- Animal and cellular models must be applied or developed to estimate cancer, CNS risks, and other risks
- Synergistic modifiers of risk from other spaceflight factors
- Shielding has excessive costs and will not eliminate galactic cosmic rays (GCR)



$\gamma$  - rays

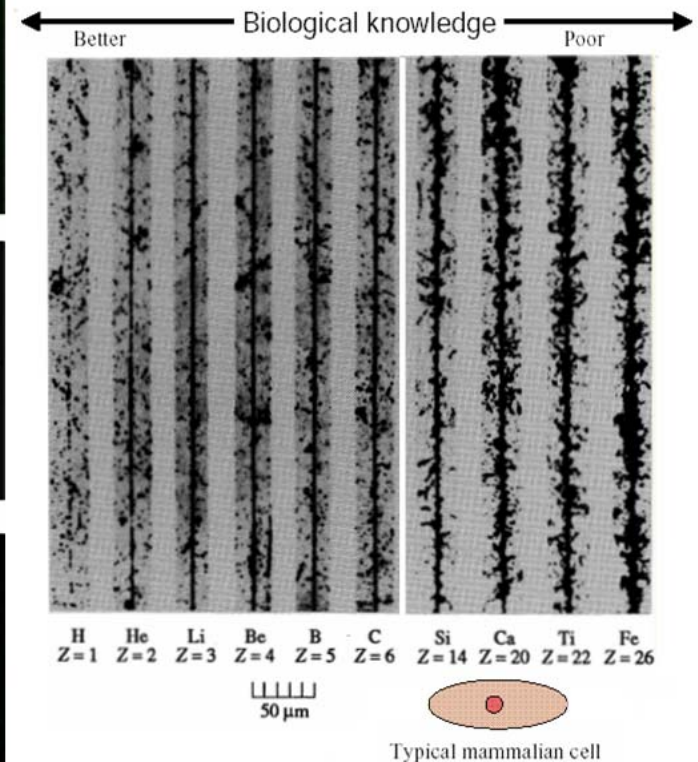


silicon



iron

Single HZE ions in cells  
And DNA breaks

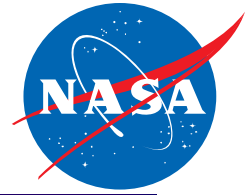


Single HZE ions in photo-emulsions  
Leaving visible images

Cucinotta and Durante, Lancet Oncology (2006)



# Space Radiation Risks



Human Research Program

- Risk of Radiation Carcinogenesis
  - Morbidity and mortality risks
- Risk of Acute & Late Central Nervous System Effects from Radiation Exposure
  - Changes in motor function and behavior or neurological disorders
- Risk of Degenerative Tissue or Other Health Effects from Radiation Exposure
  - Degenerative changes in the heart, vasculature, and lens
  - Diseases related to aging, including digestive, respiratory disease, premature senescence, endocrine, and immune system dysfunction
- Risk of Acute Radiation Syndromes due to Solar Particle Events
  - Prodromal effects (nausea, vomiting, anorexia, and fatigue), skin injury, and depletion of the blood-forming organs

## *Risks documented in HRP Evidence Reports*

### Risk of Acute or Late Central Nervous System Effects from Radiation Exposure

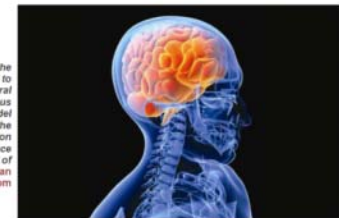
Francis A. Cucinotta  
NASA Johnson Space Center

Huichen Wang  
Emory University School of Medicine

Janice L. Huff  
Universities Space Research Association

Acute and late radiation damage to the central nervous system (CNS) may lead to changes in motor function and behavior, or neurological disorders. Radiation and synergistic effects of radiation with other space flight factors may affect neural tissues, which in turn may lead to changes in function or behavior. Data specific to the spaceflight environment must be compiled to quantify the magnitude of this risk. If this is identified as a risk of high enough magnitude, then appropriate protection strategies should be employed. – Human Research Program Requirements Document, HRP-47052, Rev. C, dated Jan 2009.

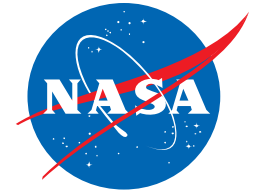
Acute and late radiation damage to the central nervous system (CNS) may lead to changes in motor function and behavioral or neurological disorders. A vigorous ground-based cellular and animal model research program will help quantify the risk to the CNS from space radiation exposure on future long distance space missions and promote the development of optimized countermeasures. © Sebastian Kaulitzki - Fotolia.com



<http://humanresearchroadmap.nasa.gov/Evidence/>



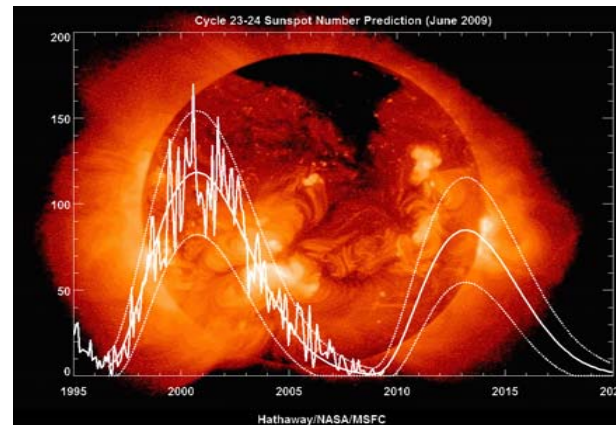
# Mitigation Approaches



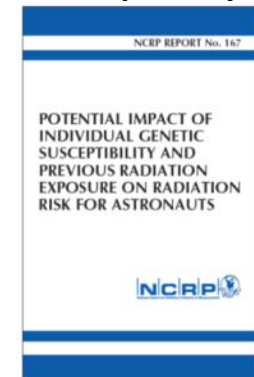
Human Research Program

- **Time in the Solar Cycle**
- **Radiation Shielding**
  - Amounts and material types
  - Design Optimization
- **Accurate Risk Quantification / Uncertainty reduction**
- **Crew Selection**
  - Age, gender, lifestyle factors, etc,
  - Individual Sensitivity (genetic factors)
- **Biological Countermeasures (BCMs)**
  - – Radioprotectors / Mitigators
- **Biomarkers predictive of radiation induced diseases**
  - Future individualized risk assessment
  - Early detection and prognostic monitoring

## Variation of Solar Activity

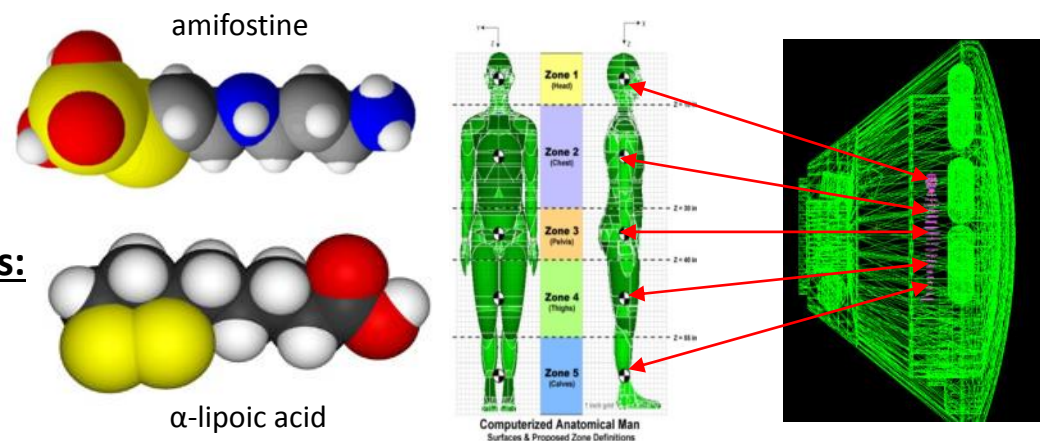


## Individual Susceptibility



NCRP 2011

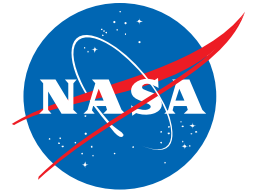
## Shield Design and Optimization



BCM: Pharmaceuticals

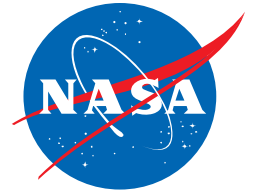
## Example targeted models to support approaches:

- Acute Radiation Risk and BRYNTRN Organ Dose Projection
- GCR Event-Based Risk Model
- NASA Space Cancer Risk Integrated Tools
- Relativistic Ion Tracks



*Human Research Program*

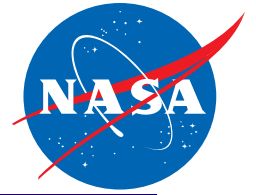
### **3. Interaction of the Human with Spacecraft and Operations**



*Human Research Program*

# Interaction of the Human with Spacecraft and Operations: Clinical physical health support from medical system

**HRP's Exploration Medical Capabilities (ExMC) Element**

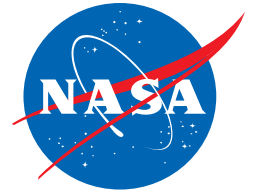


# Medical Effects in Space

*Human Research Program*

- Historical spaceflight data have revealed multiple in-flight medical events, some of which have had mission impact. While none have led to loss of crew life, there have been three non-USOS medical events leading to either evacuation or early termination of mission.
- Exploration Medical Condition List
  - Approximately 100 medical conditions of concern identified, updated annually
  - Sources include in-flight data, expert panels
  - More information publicly available:  
[https://humanresearchwiki.jsc.nasa.gov/index.php?title=Category:Medical\\_Conditions](https://humanresearchwiki.jsc.nasa.gov/index.php?title=Category:Medical_Conditions)
- Examples:
  - Space Motion Sickness
  - Space Adaptation Back Pain
  - Fingernail Delamination (EVA)
  - Kidney Stones
  - Conditions occurring in common terrestrial situations: injuries, sprains/strains, dislocations, lacerations, infections

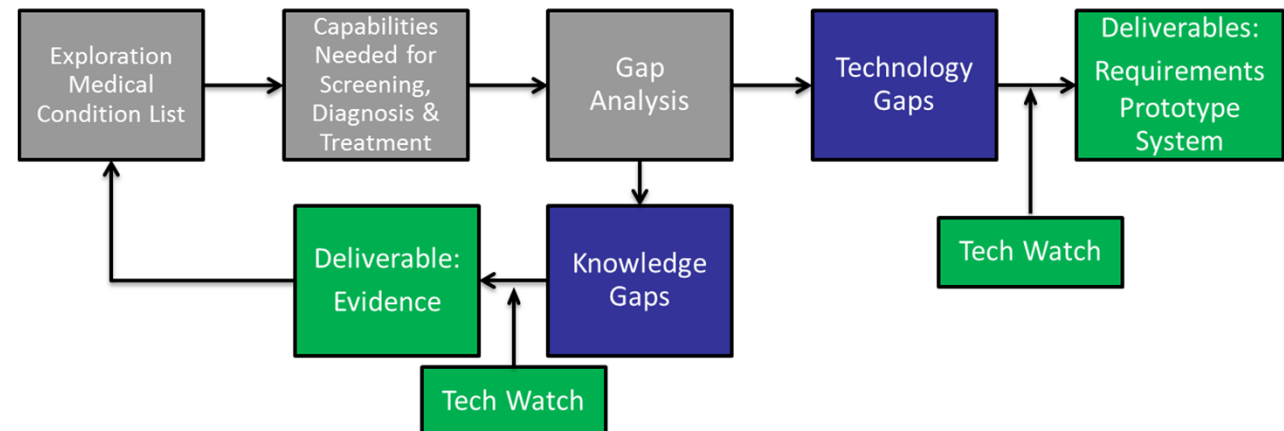




# Mitigating Adverse Medical Events

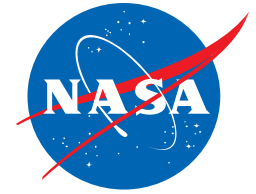
Human Research Program

- Human exploration mission systems will be restricted in the availability of
  - Medical knowledge
  - Skills
  - Procedures
  - Resources (e.g. mass, power, volume, information)
  - to optimally prevent, diagnose, and treat in-flight medical events.
- Ideally, spaceflight medical capability will approach terrestrial standards of care.
- The strategy for mitigation of medical risks focuses on:
  - Prevention
  - Screening
  - Diagnosis
  - Treatment





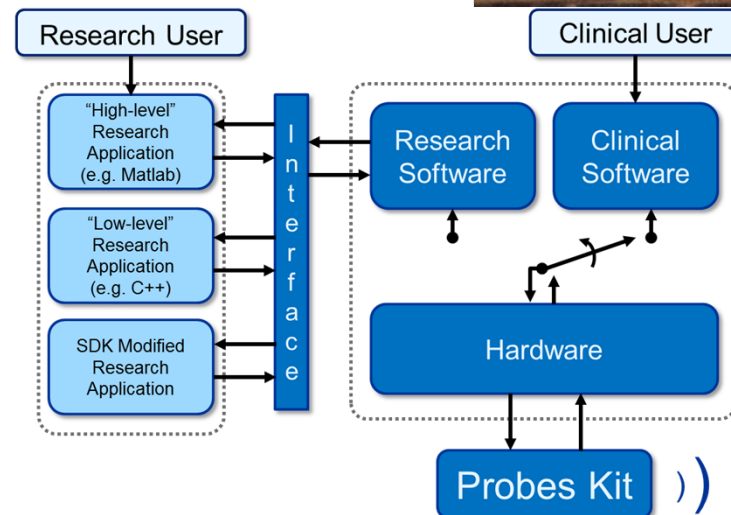
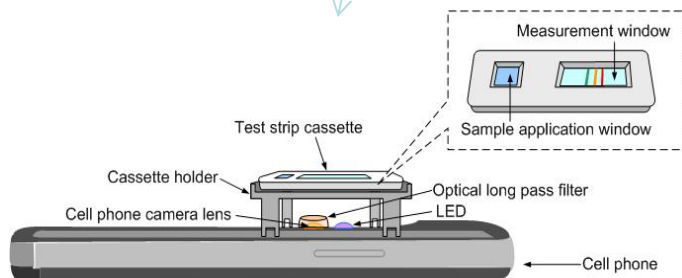
# Countermeasures for Spacecraft and Operations

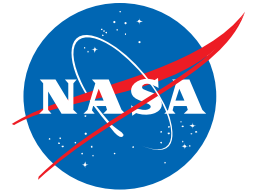


Human Research Program

- Crew training, screening, selection, treatment
- Current or planned technologies:

- Oxygen concentrator
- Dry electrode ECG
- Integrated medical data management system
- Medical consumable tracking system
- Flexible ultrasound
- Laboratory Analysis





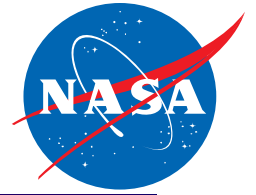
*Human Research Program*

# Interaction of the Human with Spacecraft and Operations: Physical and cognitive performance support from system interfaces

**HRP's Space Human Factors and Habitability  
(SHFH) Element**



# Human Factors & Habitability Effects in Space

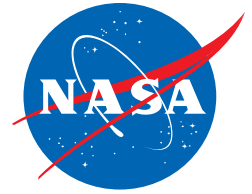


*Human Research Program*

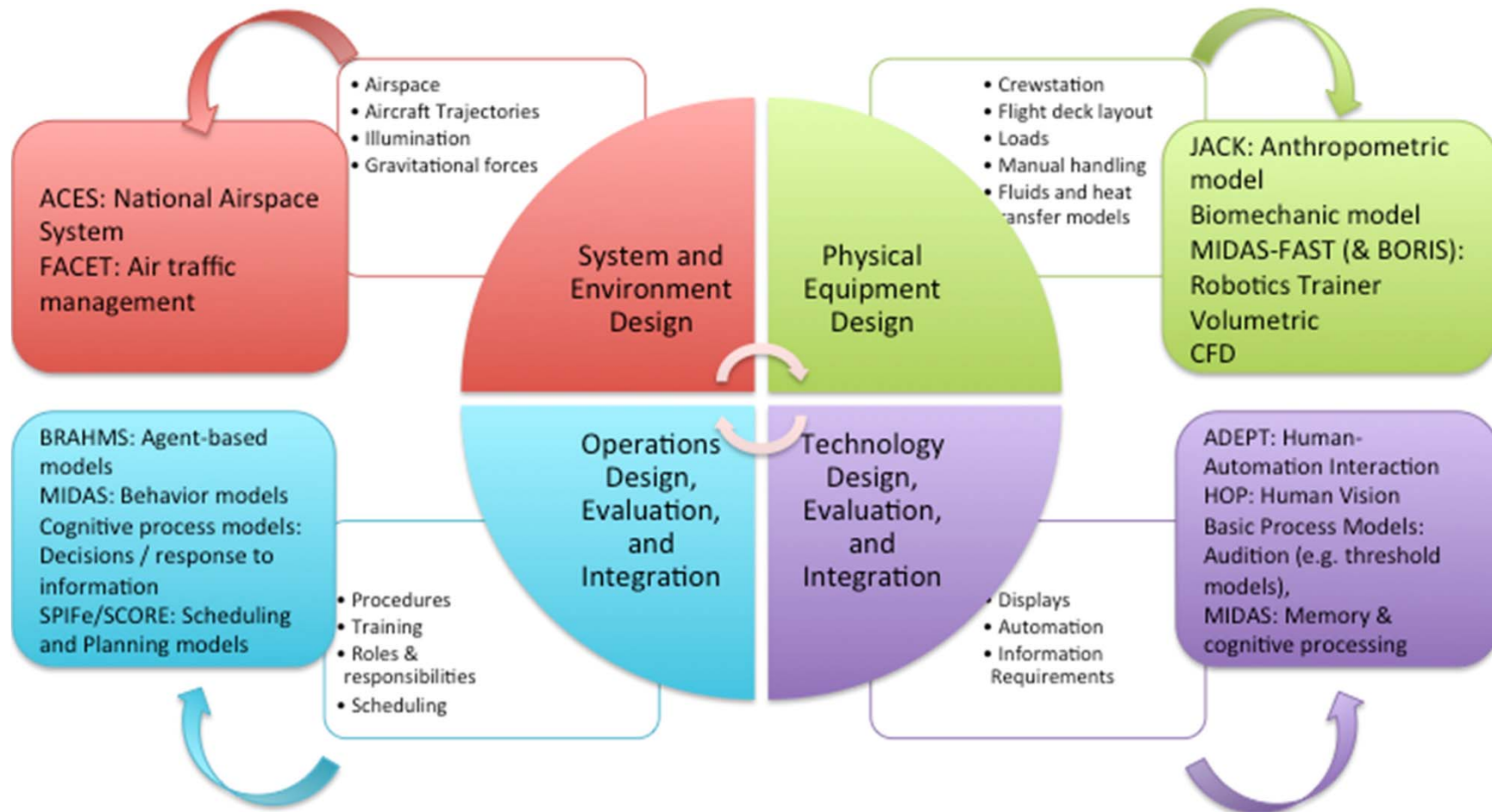
- Spaceflight environment → changes in human capabilities and limitations
  - Physical performance (e.g. reach)
  - Cognitive performance (e.g. task and procedure performance)
- Changes can be due to
  - Physiological adaptations as described earlier
  - Incompatible vehicle/habitat design
  - Inadequate design of human and automation/robotic integration
  - Inadequate human-computer interaction
  - Inadequate critical task design
  - Training deficiencies
- Mitigation approach
  - Identify design requirements for the environments and systems, and develop methodologies to determine, assess, and validate these requirements
  - Influence design of spacecraft, equipment, and tasks for future exploration missions
  - Improve existing and new system development by providing affordable and practical tools, processes and metrics



# Human Modeling in System Design



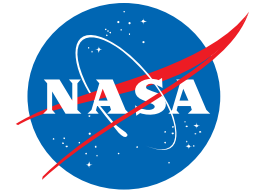
Human Research Program





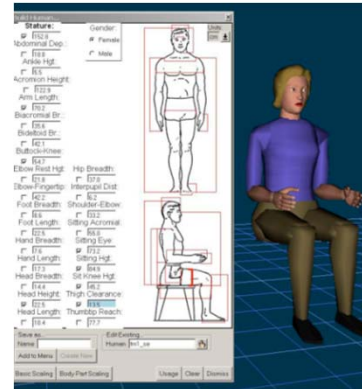
# Human Factors & Habitability

## Targeted Model Examples

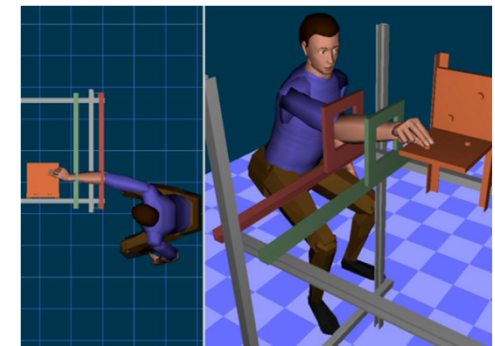


Human Research Program

- Physical environment interfaces
  - Static human models
  - Human performance models
- Physical and operational environment interfaces
  - MIDAS (Man-machine Integration Design and Analysis System)
    - Human perception, visual attention, memory, workload
    - Workstation, equipment, environment
    - Produces task timelines, workload, situational awareness profiles
  - Computational model for spacecraft habitable volume (new project)
    - Volume drives spacecraft mass and cost
    - "Bottoms up" based on mission attributes and critical task volumes to determine appropriate volume



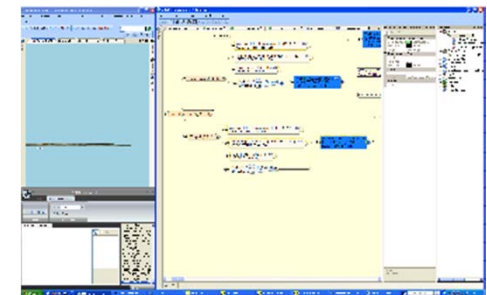
Static model



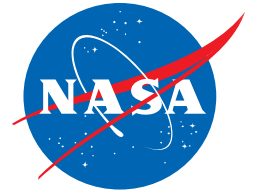
Simulation-based model of reach and access



MIDAS



@AstroRM: "In my crew quarters on station. 3'x3'x6.3' I barely fit but it is home. I have my sleeping bag and computer and pics"



*Human Research Program*

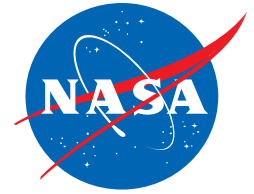
## **4. Areas of Convergence and Integration**





# Cross Disciplinary Touch Points

Based on Program Research Plan Analysis



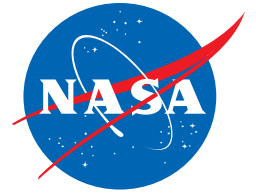
Human Research Program

	<i>Bone</i>	<i>Muscle</i>	<i>Aerobic</i>	<i>Cardiovascular</i>	<i>Behavior/ Performance</i>	<i>Sensorimotor</i>
<b>Bone</b>						
<b>Muscle</b>	Fitness					
<b>Aerobic</b>	Fitness	Fitness				
<b>Cardiovascular</b>	Inflammation	Fitness	Fitness			
<b>Behavior/ Performance</b>	Inflammation	Mood	Cognition	Stress		
<b>Sensorimotor</b>	Fatigue Failure	Fitness	Fitness	Fluid Shift	Cognition	

S. Steinberg 2014



# Countermeasures

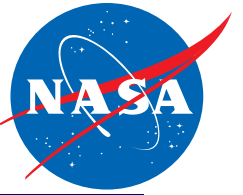


Human Research Program

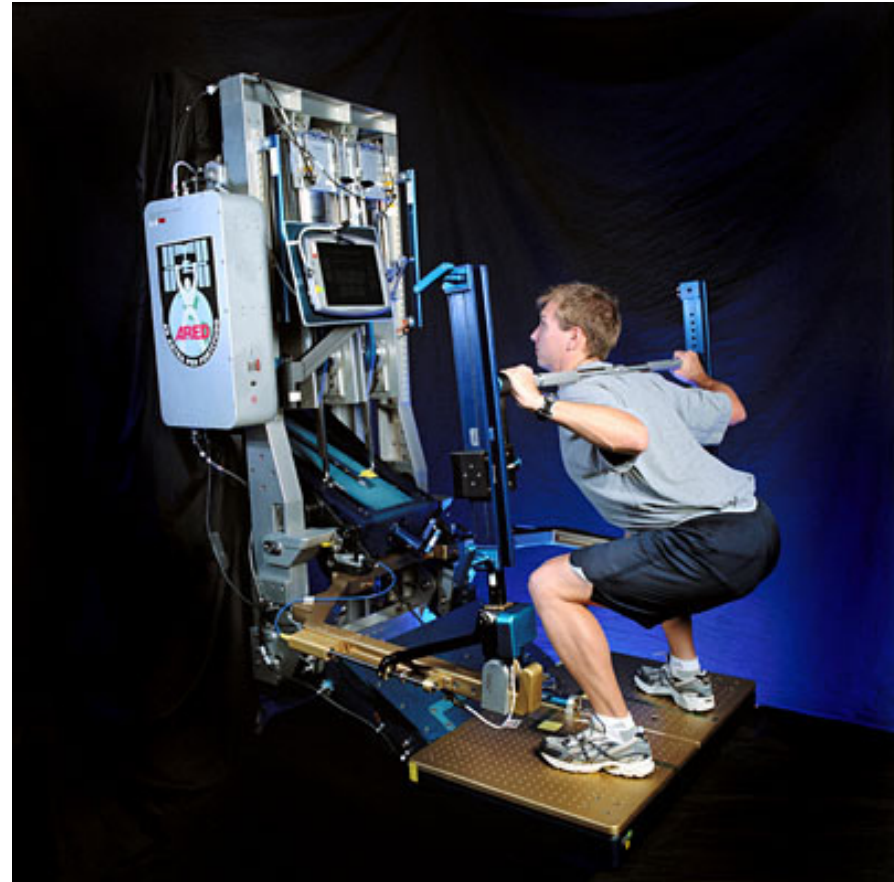




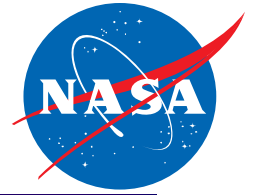
# Countermeasure Example: Advanced Resistive Exercise Device (ARED)



*Human Research Program*



Effective but too big to take to Mars



# Orthostatic Intolerance

Human Research Program

- Mitigated by:
  - Oral salt and fluid loading
  - Antigravity garment
  - Additional clinical i.v. fluid treatment

Platts et al. 2012







# Integrated Physiological Countermeasure Suite

---

## **Pre-flight**

- Establish healthy life style: Exercise, food intake
- Develop individualized CM-protection programs: Computer modeling, G-transition training

## **In-flight**

### Monitoring

- Immune/OSaD biomarkers (Lab analysis of urine, blood, saliva)
- Cardiovascular, VIIP, muscle/bone (ultrasound, ECG, BP, OCT, CCFP/TCD, vision, cognition)

### Training & Prevention

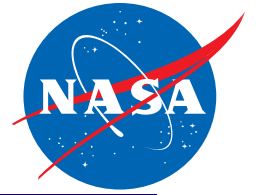
- Sensory-motor adaptability training: Computer programs , vestibular (galvanic) stimulation
- Exercise prescriptions: Aerobic and resistive
- EVA pre-breathing
- Functional food items: Omega-3, anti-oxidants, low salt and iron
- Anti-osteoporotic medications: Bisphosphonates, anabolics, ACE-inhibitors

### Treatment and prevention

- Anti-VIIP bracelets (+/- dynamic exercise) and/or medication
- Anti-motion sickness & anti-inflammatory medications (medication stability monitoring)
- Anti-orthostatic pre-landing fluid and salt ingestion

## **Planetary landing:**

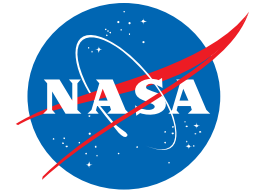
- Anti-orthostatic garment and fluid/salt treatment
  - G-transition medication, vestibular (galvanic) stimulation
-



# Nutrition and Food

*Human Research Program*

- Nutrition influences crew health, including:
  - endurance, muscle mass and strength, immune function, bone mass and strength, cardiovascular performance, gastrointestinal function, endocrine function, and ocular, psychological and physical health, ability to mitigate oxidative damage, and prevent disease
- Provision of nutrients in safe amounts (neither high nor low) depends on
  - providing appropriate, palatable, foods with the stability of nutrients for the duration of the mission
  - actual intake of the nutrients
  - knowledge that countermeasures are not altering requirements
- Food must be free from microbiological, chemical, and foreign matter contamination for up to five years of storage for extended duration missions
- Acceptable food (texture, appearance, flavor, aroma, and temperature) for up to five years
  - encourages consumption
  - boosts crew morale by alleviating boredom and stress
  - promotes unity amongst the crew during meal time
- Must use resources efficiently to implement:
  - mass, volume, power, crew time, and waste disposal capacity

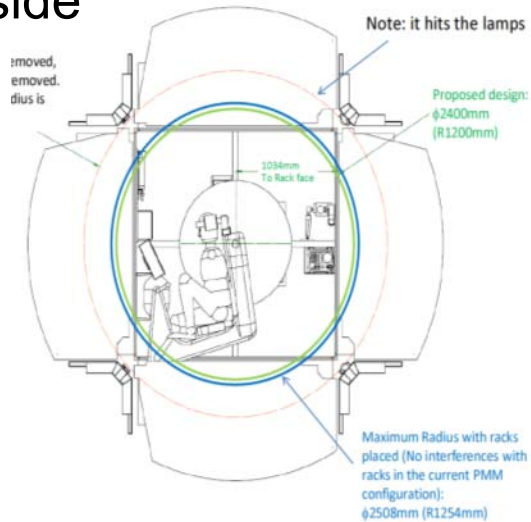


# Artificial Gravity

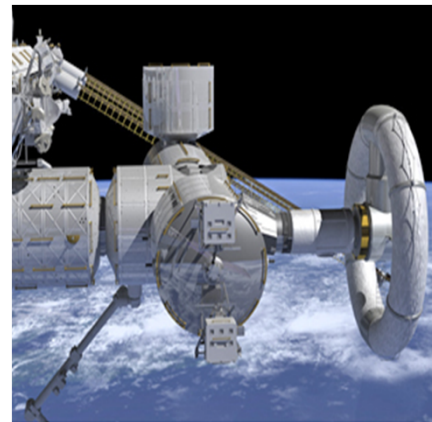
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## Spinning options:

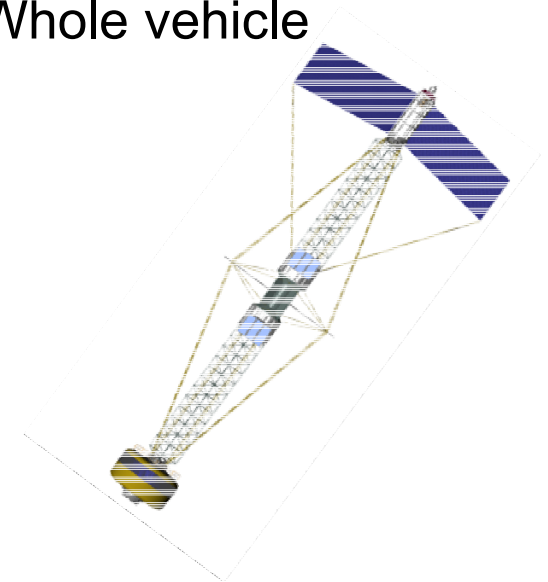
Inside



Part of

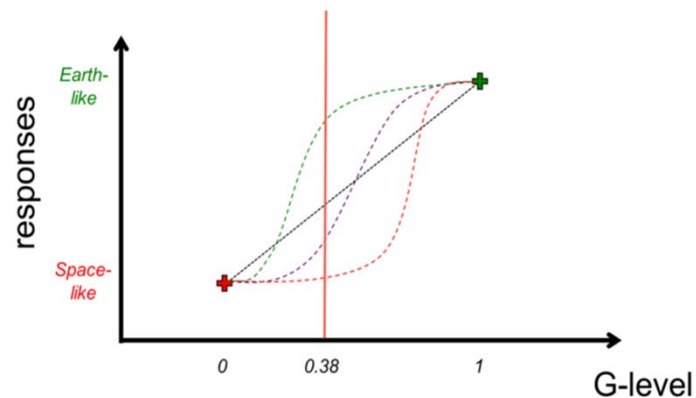


Whole vehicle



## We don't know:

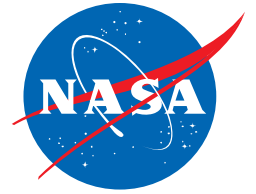
*Physiological Responses to Hypogravity?*



- The minimum artificial gravity level?
- The protection of Martian gravity?

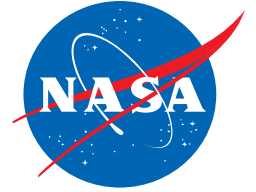
Paloski 2014





*Human Research Program*

## **5. Approaches to Integration and Modeling**



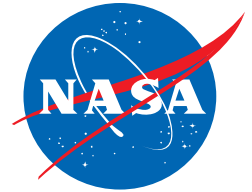
*Human Research Program*

# Detailed Mathematical Modelling: Digital Astronaut Project

HHC Intra-Element/P. Norsk

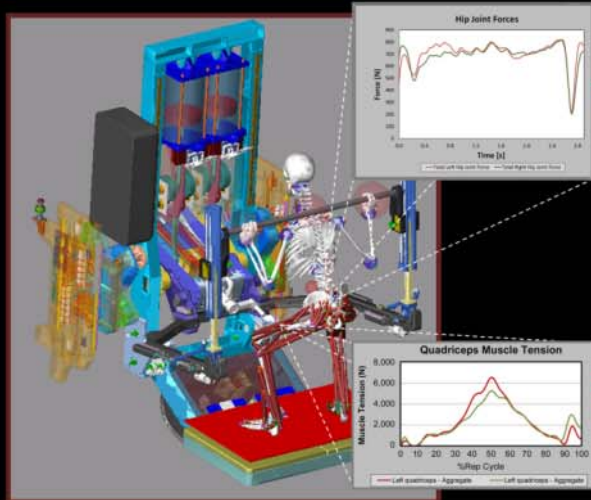


# Computational Modeling to Preserve the Musculoskeletal Health of Astronauts



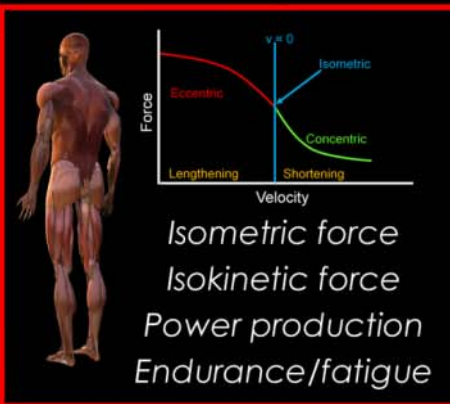
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## Simulation of Exercise Countermeasure



Muscle force & joint load

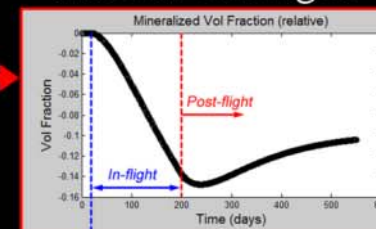
## Simulation of Muscle Adaptation



Insight into efficacy of exercise protocol to maintain bone

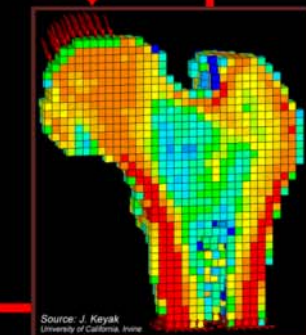


## Simulation of Bone Mineral Changes



**In-flight:** Help minimize bone strength loss

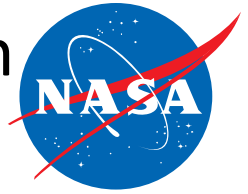
**Post-flight:** Help improve regain of bone strength & help reduce lifetime bone health risk to astronauts



Predict Bone Strength Changes

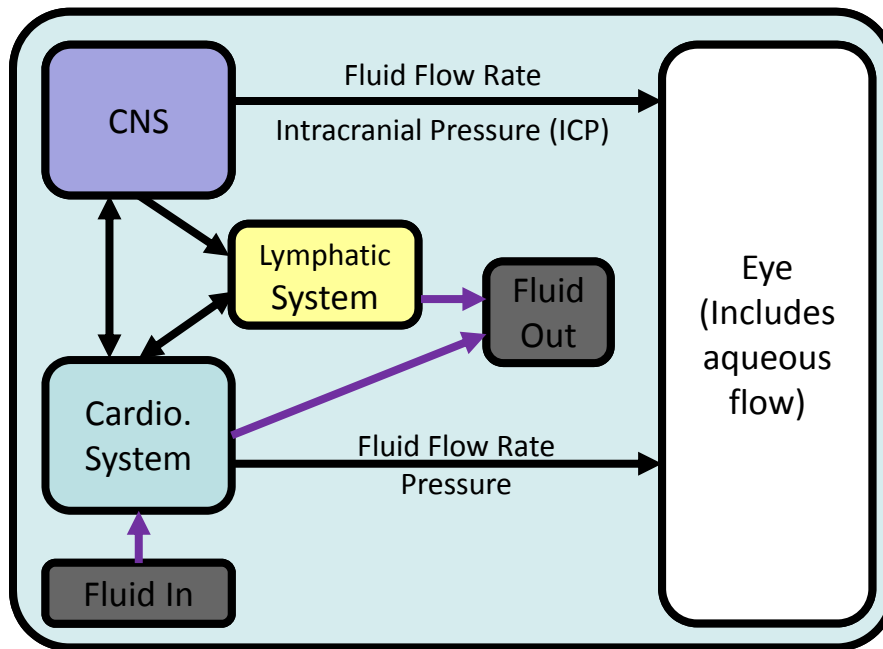


# Computational Modeling to Preserve the Vision Health of Astronauts

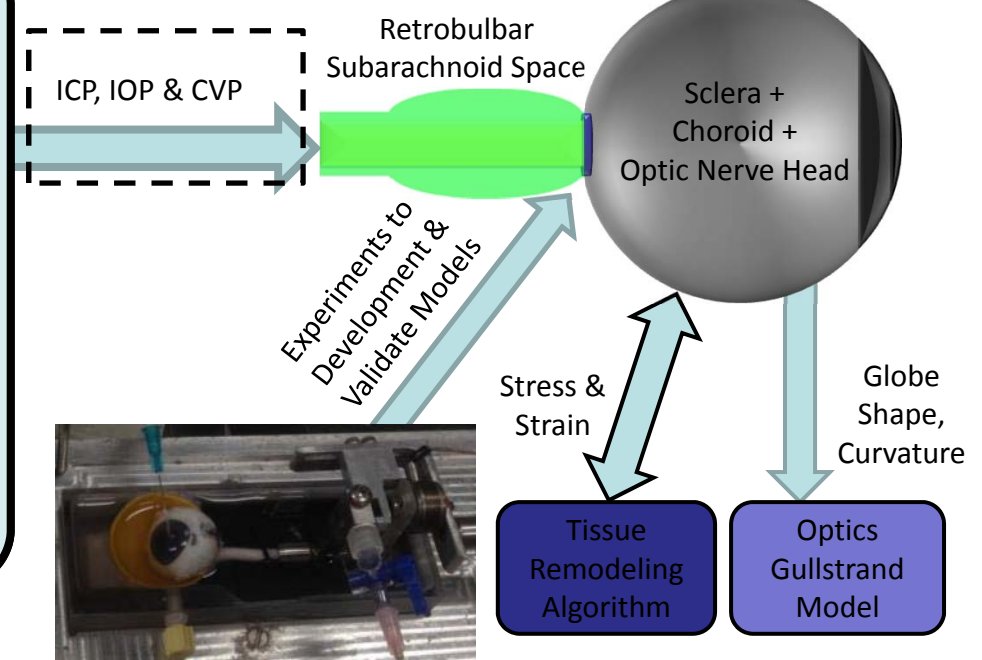


Human Research Program

## Linked Lumped-Parameter Models



## Integration of models

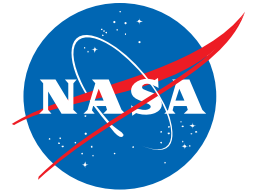


## Models can be used to assess the role of:

1. Vascular, cranial/spinal and ocular fluid volumes, compliances and resistances on IOP and ICP
2. Microgravity-induced cephalad fluid shift on ICP and IOP
3. Chronic and multiple exposures to microgravity

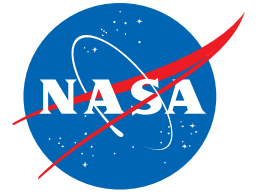
## Experimental measurements to acquire data on:

- biomechanical properties (stiffness) of ONS pia and dura maters
- fluid permeation across ONS (preliminary results show noticeable permeability)



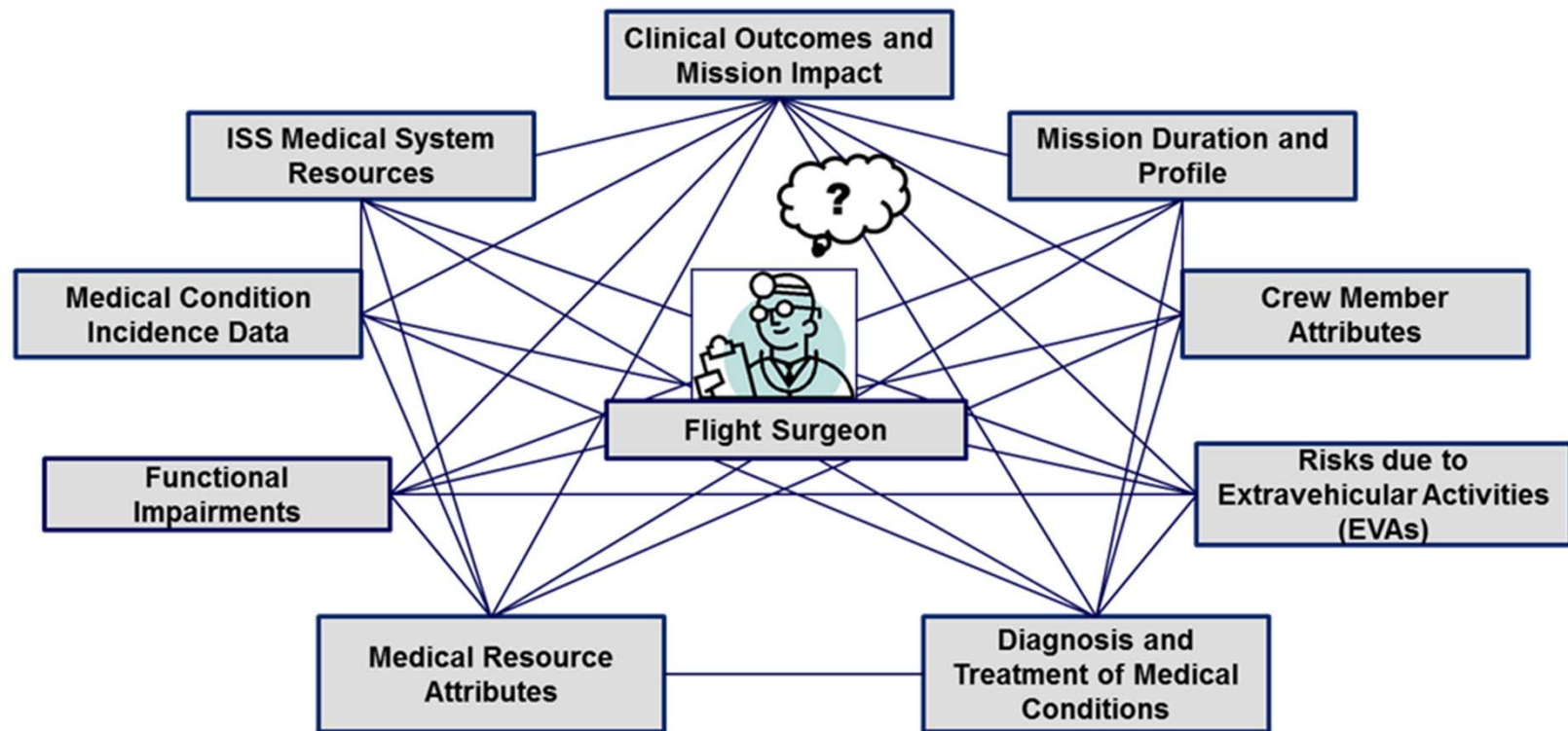
*Human Research Program*

# Probabilistic Risk Assessment Approach: Integrated Medical Model (IMM)



# IMM Current Modeling Efforts

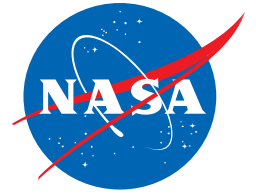
Human Research Program



- The Integrated Medical Model (IMM) has been developed to support quantifying how ExMC factors influence in-flight medical risks.



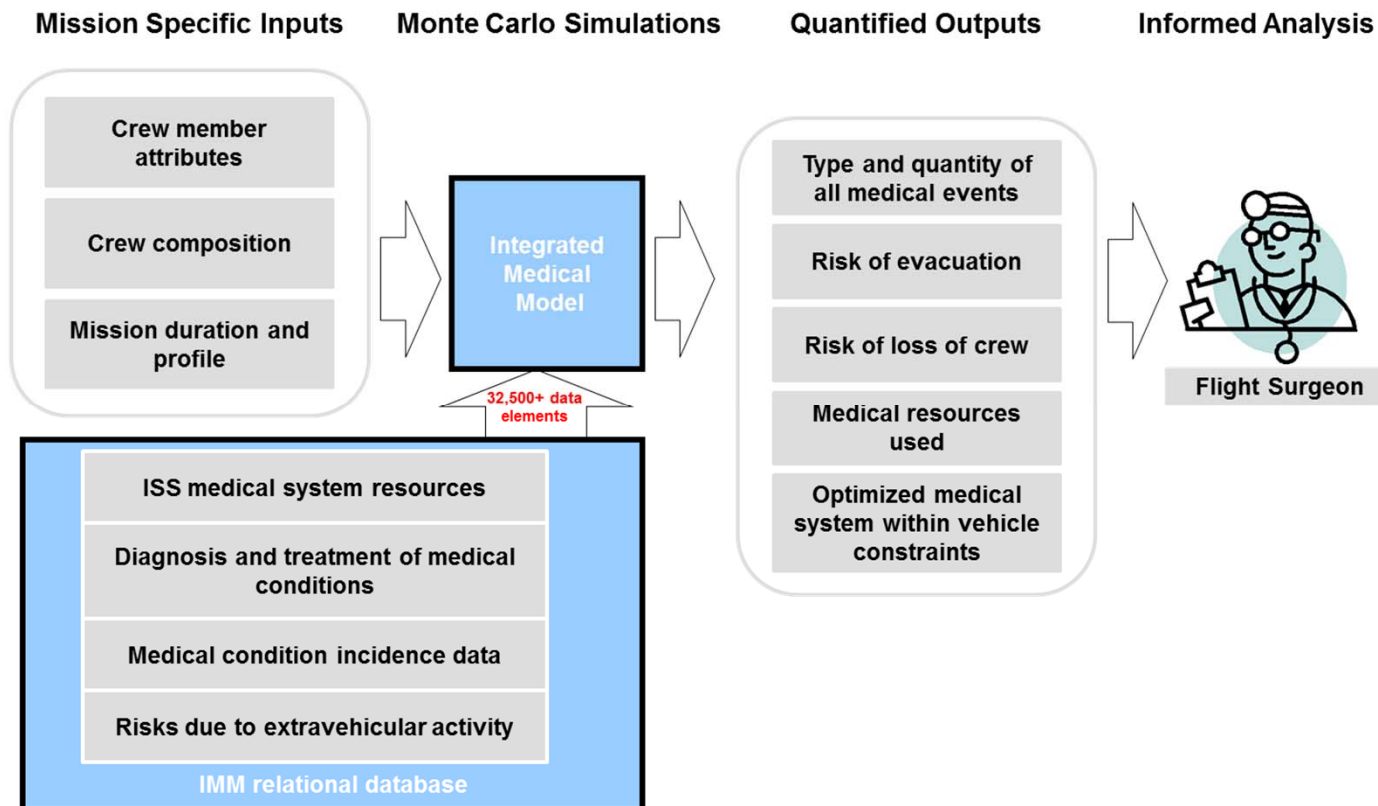
# IMM Framework



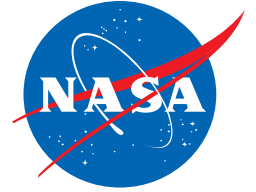
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IMM is a risk forecasting decision support tool, which simulates medical event occurrences and impacts during space flight missions and can be used to optimize the medical system within the constraints of the space flight environment.

Approach: Employ best-evidence clinical research methods, probabilistic risk assessment (PRA) techniques







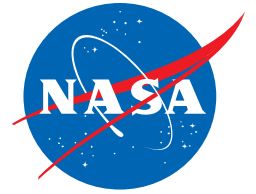
*Human Research Program*

## High Level of Abstraction Approaches: Contributing Factor Map, Networks

- Can these tools help us understand the state of human adaptation in space?
- Can they help us assess and promote resilience?

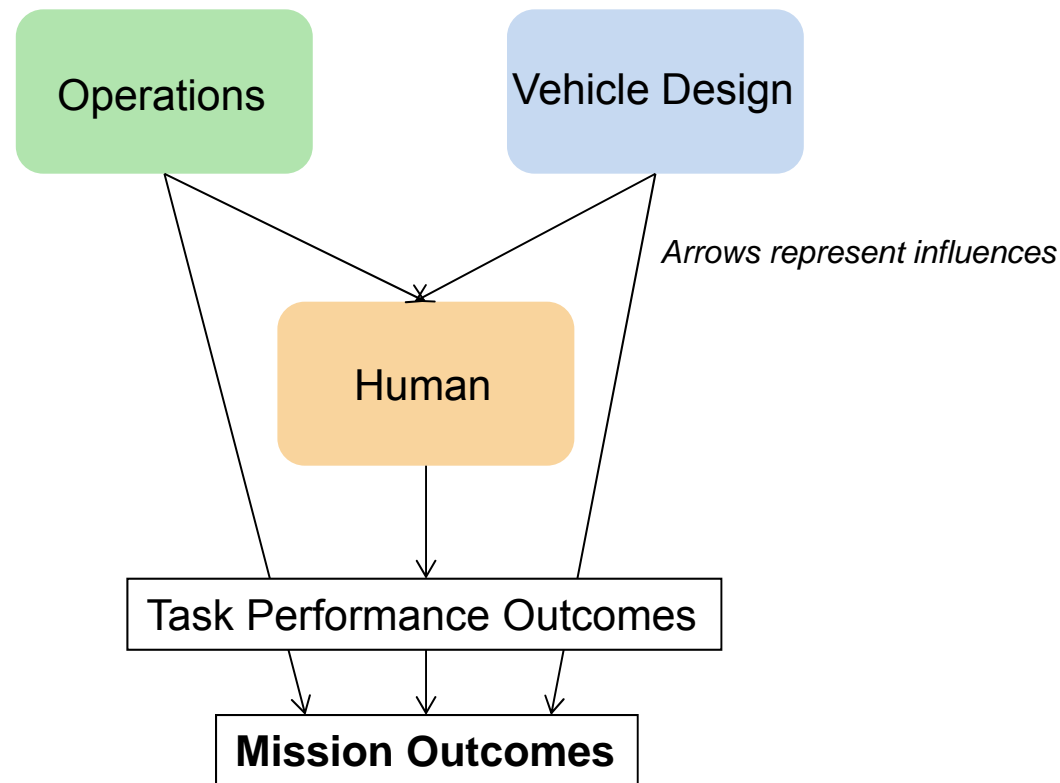


# System of Systems Interact



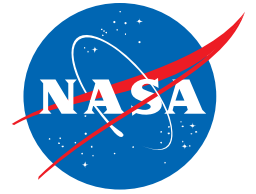
Human Research Program

- Common goals of safe, productive and reliable human space flight
- Whether focus is on Operations, Vehicle Design or the Human System
- All interact as a system of systems



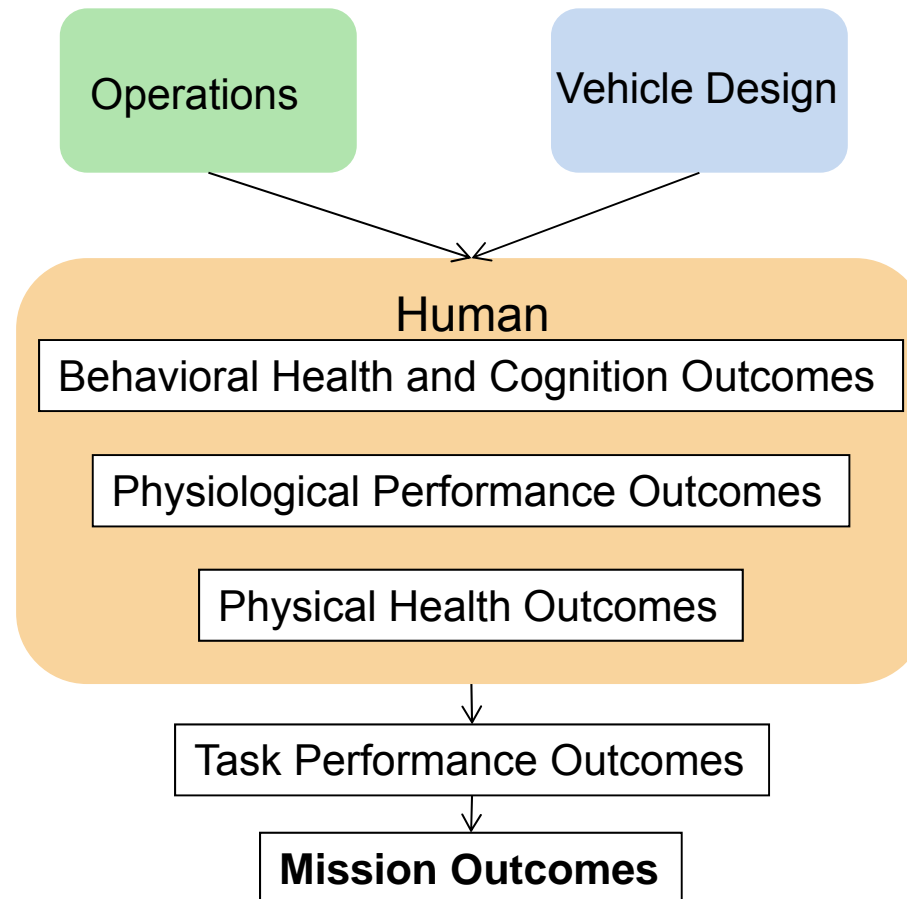


# Outcomes within Human System



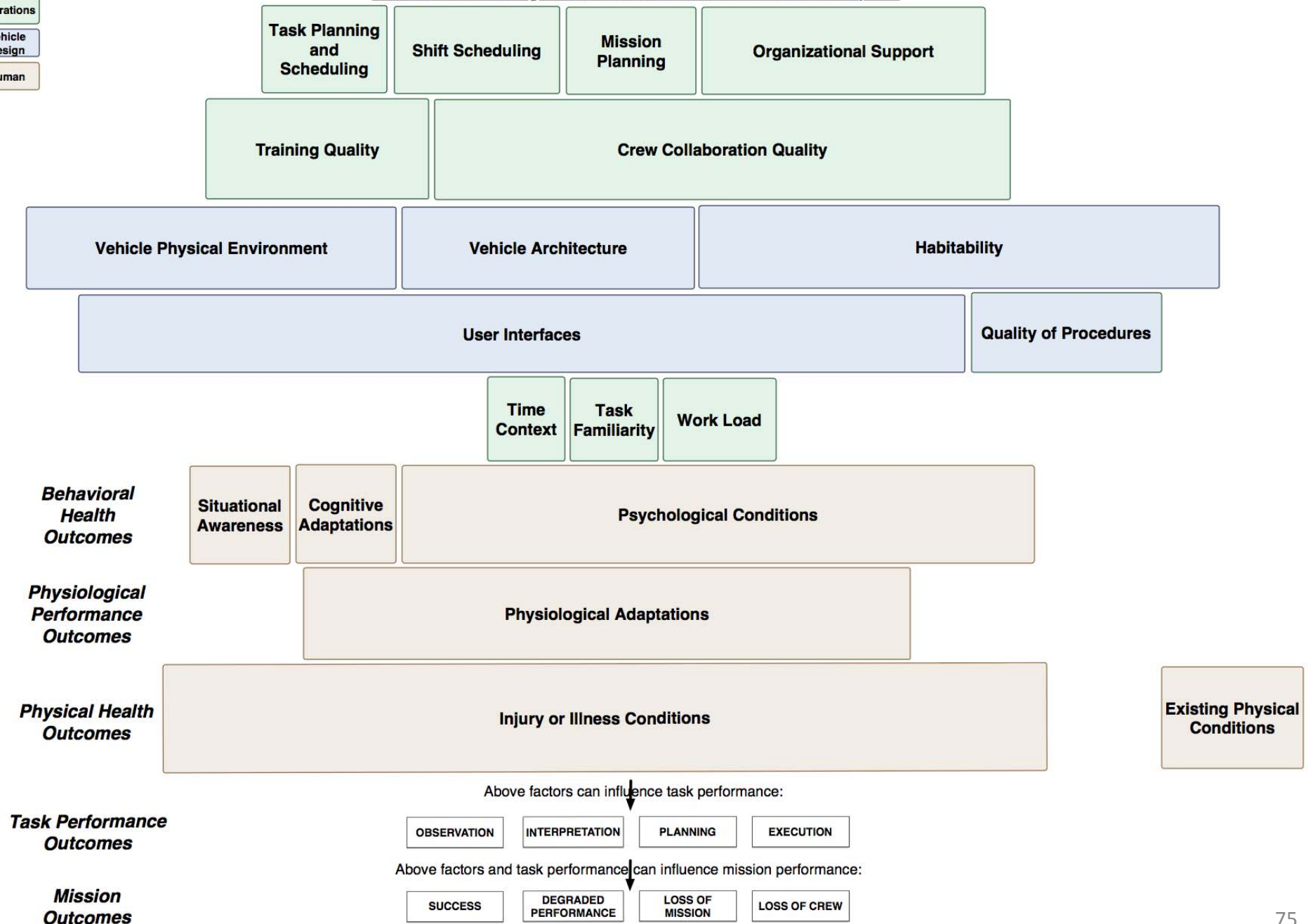
Human Research Program

- In the Human System, HRP supports the protection of additional outcomes



## Contributing Factor Map

### Factors Influencing Human Health and Performance in Space

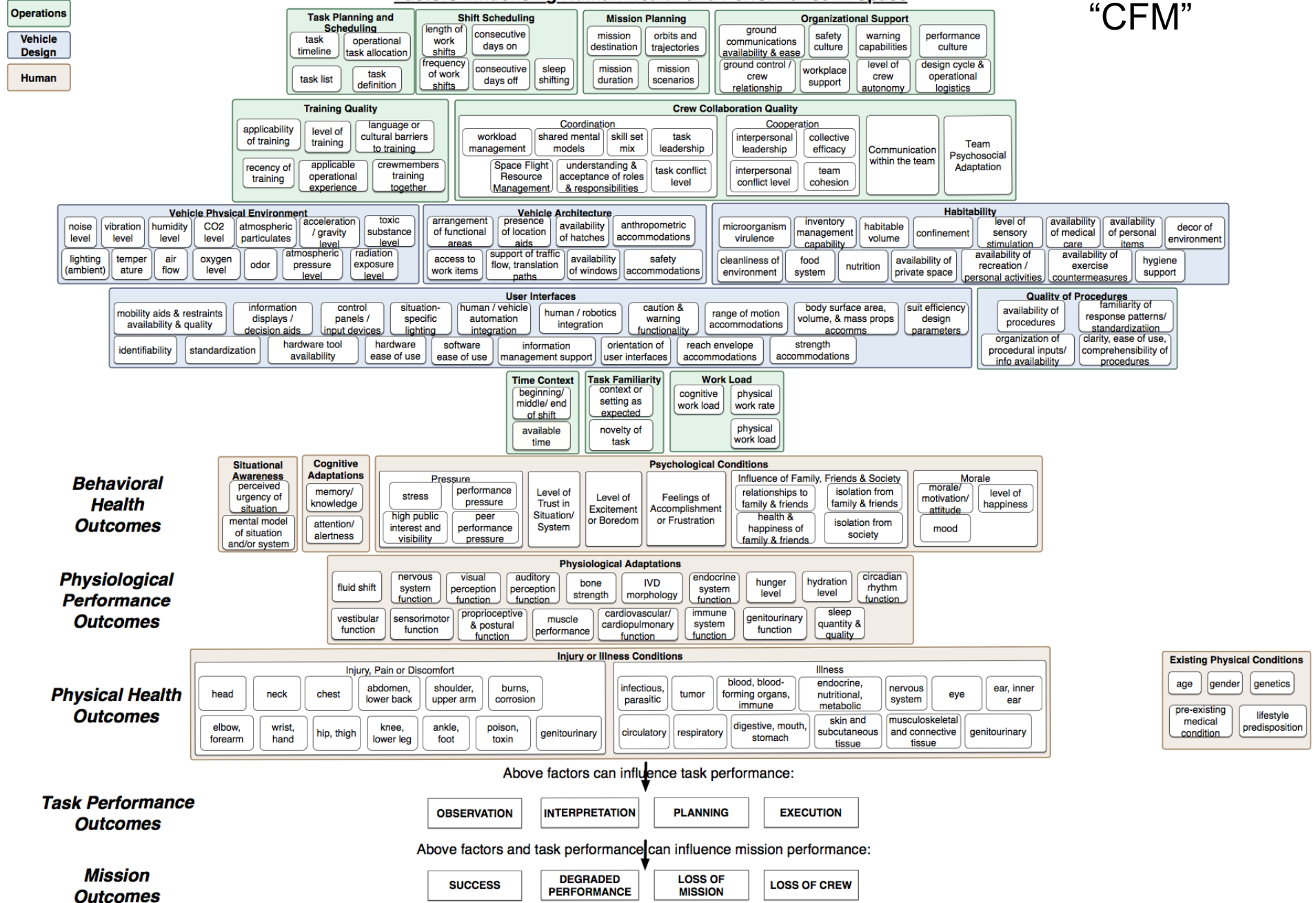


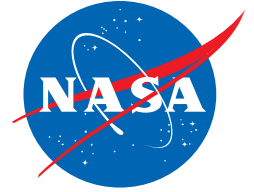
## Contributing Factor Map

9/5/13

### Factors Influencing Human Health and Performance in Space

“CFM”



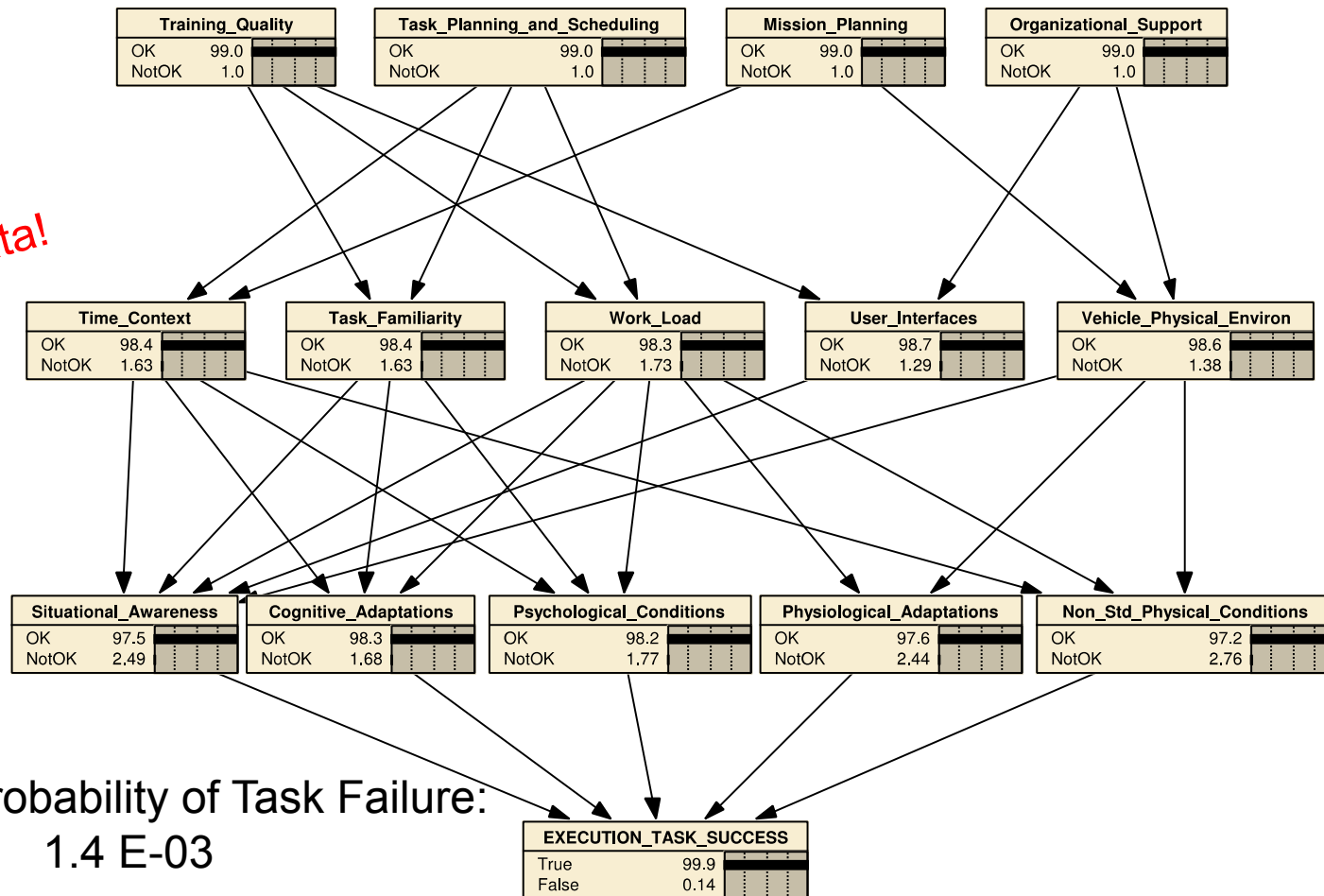


# Conceptual Approaches - Networks

Human Research Program

Sensitivity analysis on a Bayesian Network model such as this can be performed to identify areas of high influence.

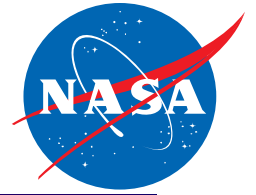
Not real data!



Example Probability of Task Failure:  
1.4 E-03



# Conceptual Approaches – Small World Networks



Human Research Program

- Gain understanding of nodes of importance (hubs)
- Analyze behavior (resilience of system) when various nodes are removed or altered
- Potentially map time-series data to network
- Compare “healthy” vs. “unhealthy” systems

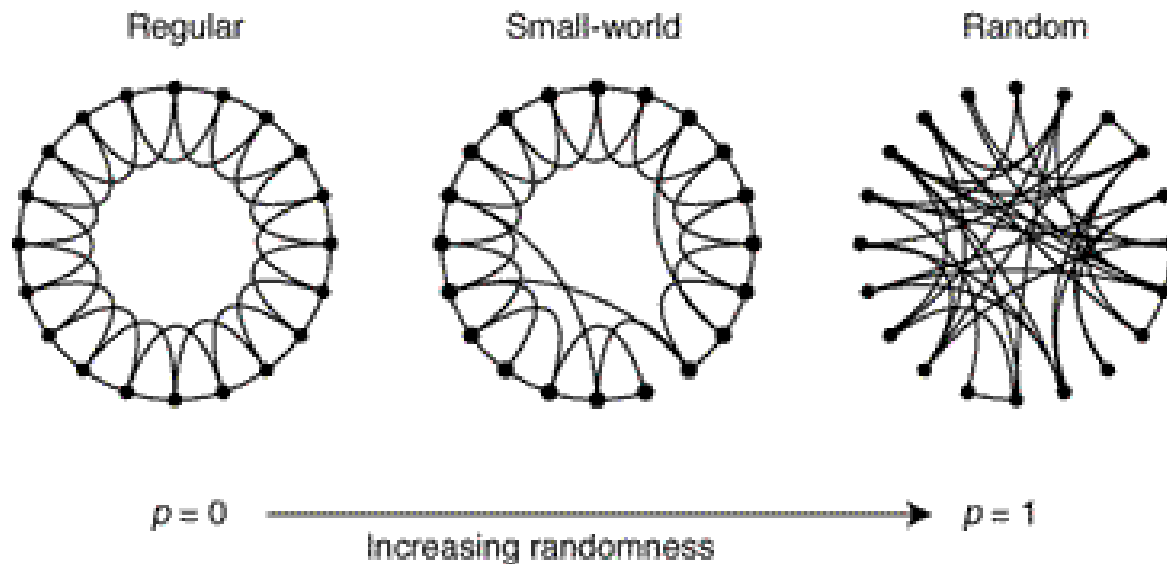
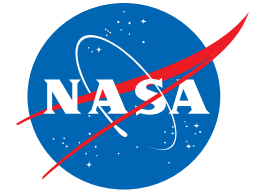


Fig. 1 from: Watts and Strogatz, "Collective dynamics of 'small-world' networks," *Nature*, vol. 393, p. 440-442, 4 June 1998.



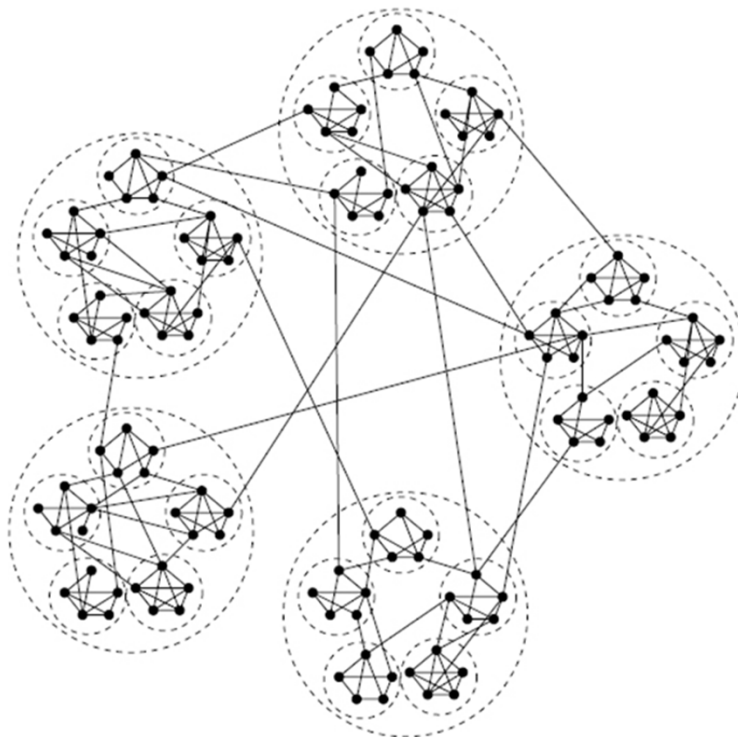


# Initial Efforts

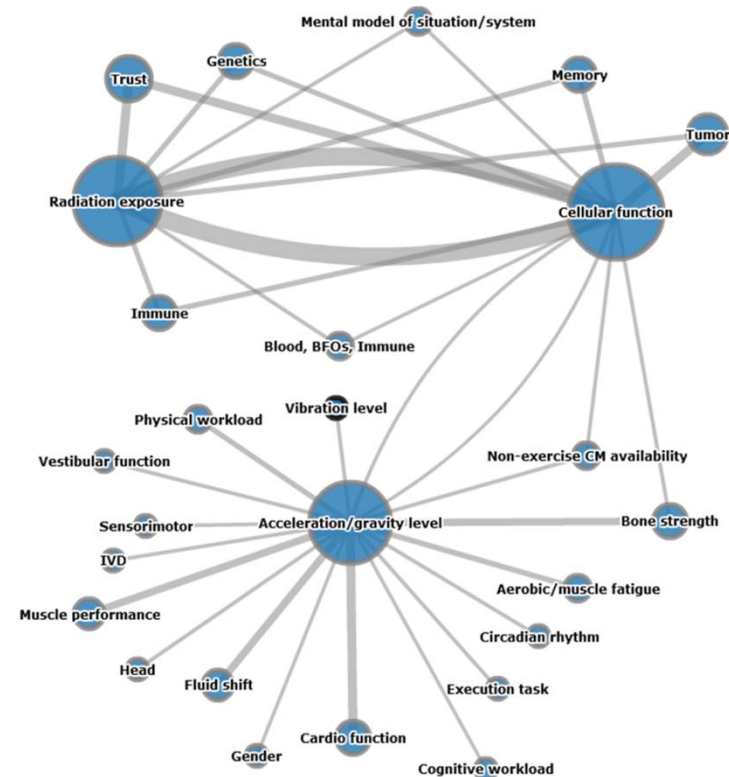
Human Research Program

- Developing visualizations of linkages between topics covered by existing NASA Human Research Program work based on publication records

*Small World Network conceptual example*

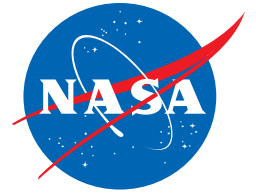


*Proof-of-concept network based on a subset of HRP publications*



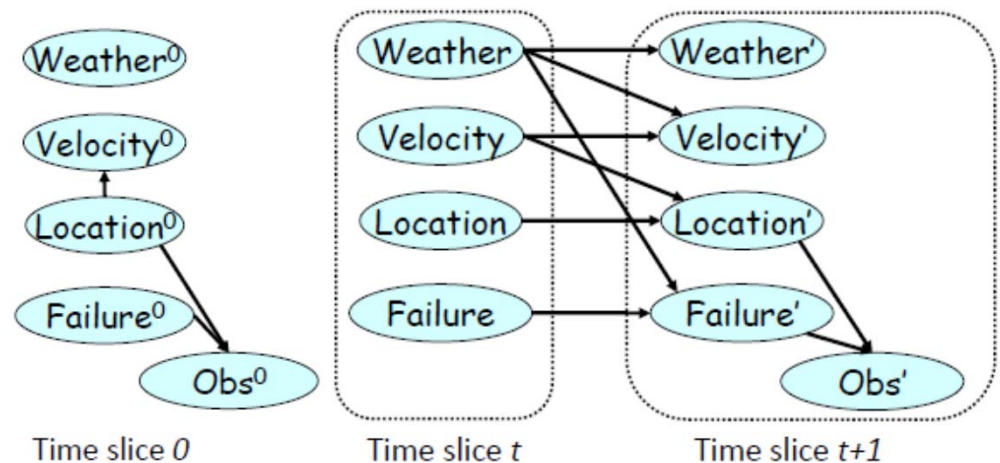


# Networks



Human Research Program

- Dynamics on networks
  - Stable states
- State transitions on networks
  - Movement between stable and transitional states
- Self-organization
- Resilience



Images: D. Koller Probabilistic Graphical Models course  
<https://www.coursera.org/course/pgm>

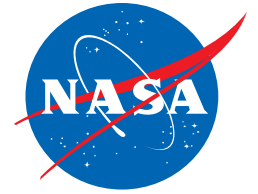


# The Big Picture

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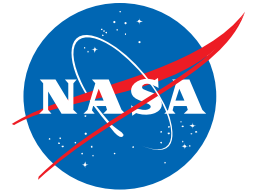


- Need to better understand human adaptation to space
    - ✓ Provide better countermeasures
      - Integrated approaches to minimize resources
    - ✓ Provide tools for autonomy
    - ✓ Assess and maintain resilience
      - Individual
      - Team
  
  - Advantages
    - ✓ Relatively homogeneous, motivated, well-characterized subjects.
    - ✓ Well-defined and characterized environment.
    - ✓ Subject compliance rarely an issue.
  
  - Disadvantages
    - ✓ Small population
    - ✓ Not analogous to terrestrial populations on Earth
-



*Human Research Program*

# Backup



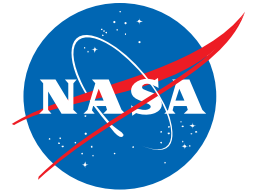
# Potential Collaboration Questions

*Human Research Program*

- 1) Does “space normal” – the tendency of the multiple subsystems to reach stable plateaus during long-duration flights – represent a new attractor state of a dynamical system, or is space normal a driven state maintained by chronic perturbation with significant dissipative costs – a form of accelerated aging?
- 2) How does a complex system, including physiological systems and technological environments, adapt when faced with chronic environmental stressors?
- 3) Is there a “common currency” through which the different bodily subsystems and their interactions can be described (e.g., metabolic energy, Gibbs free energy)?
- 4) Can the human response to space flight be characterized, at least in part, by dynamic bidirectional interaction with the environment (in the same sense that evolutionary adaptation might be characterized by information exchange between organism and environment)?
- 5) What are the best interventions and mechanisms of control to ensure continued health and productivity in the astronaut population? This might involve a range of interventions from exercise through video games.



# Sleep in Spaceflight Analogs



Human Research Program

## ***Mars 520-d mission simulation reveals protracted crew hypokinesia and alterations of sleep duration and timing (Basner et al., 2013)***

Overall, sleep increased over the duration of the mission, however, 4 of 6 crewmembers experienced one or more of the following problems:

- Disrupted sleep-wake periodicity (n=1)
- Increased displacement of sleep into day (n=2)
- Performance deficits associated with chronic partial sleep deprivation (n=1)
- Frequent reductions in perceived sleep quality (n=2)

Actigraphy data also revealed progressive sedentariness of crew: increased sleep and rest times and decreased active wakefulness with time in mission

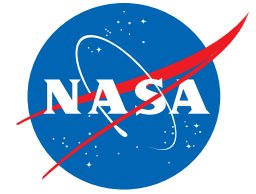
Investigators currently evaluating sleep and circadian data relative to other behavioral outcomes (e.g., conflict)







# Countermeasures – Behavioral Health



Human Research Program

## Stress Management and Resilience Training for Optimal Performance (SMART-OP) - PI: Dr. Raphael Rose

### Task Aims:

- Evaluate SMART-OP's effectiveness and usability (n = 48 NASA JSC flight controller trainees compared with a wait-list control group)
- Collect objective data of acute and chronic stress markers before and after 6 weekly sessions of SMART-OP training

### Rationale:

- Stress was identified as a potential contributor to poor flight controller trainee performance
- First study to examine the effects of self-guided stress management and resilience training on biomarkers for stress (e.g., cortisol, neuropeptide Y) and heart rate (with HHC)

**Deliverable:** a self-directed, autonomous, interactive multimedia program for stress management

## Cognition (formerly NeuroCATs) (NSBRI) Dr. Mathias Basner

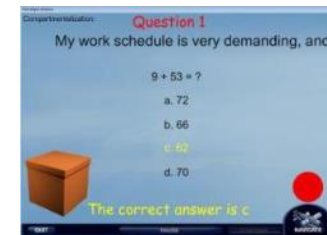
Development of normative database - ground study (12 mission controllers and 12 astronauts) and pilot ISS flight test (Inc. 41/42; n=6 astronauts)

Tool validation

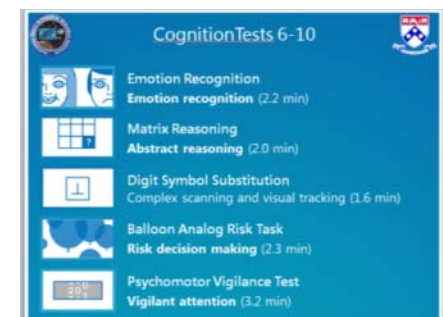
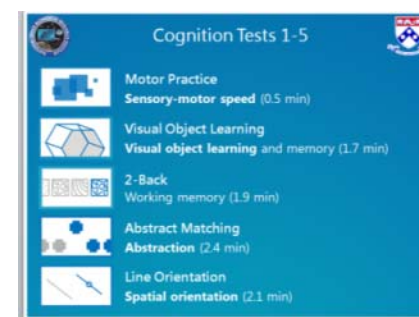
Clinical validation study (U. Penn)

HERA study

ISS one-year study



SMART-OP Screenshots of Focused Breathing, Effective Communication and Compartmentalization modules

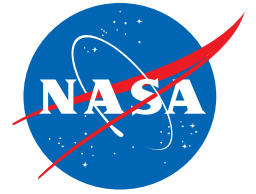


Summary of Cognition test battery



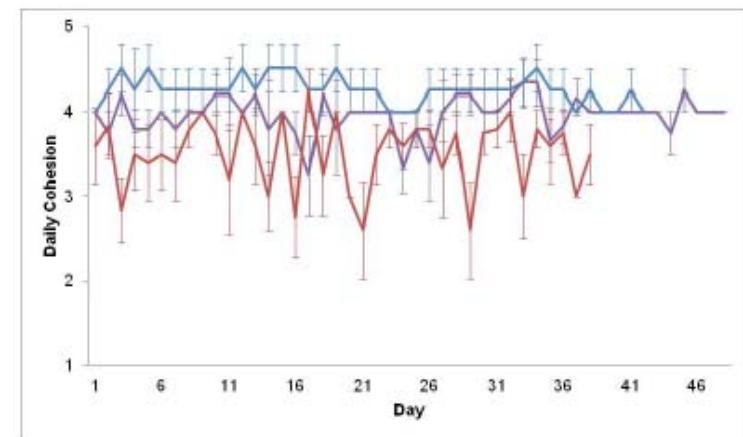


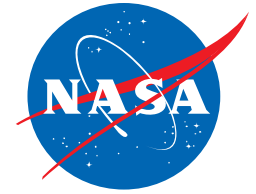
# Countermeasures - Team



Human Research Program

- **Team Dimensional Training** – Kim Smith-Jentsch, University of Central Florida
  - Study of 23 flight controllers evaluated feasibility and effectiveness of a new team debriefing strategy for use by flight directors
  - Likely the largest debrief dataset ever collected (39 simulation debriefs, over 100 participants)
  - Results indicate the debrief was effective in increasing flight controllers' team and technical learning
  - Led to 50% reduction in time to certification
- **Just in Time Training Development** - Sowmya Ramachandran, Stottler-Henke Associates, Inc.
  - Serious Games for Team Training
  - Development of a flexible software training platform for just-in-time teamwork skills training
- **Sociometric Badge Study (NRA)** – Steve Kozlowski, Michigan State University
  - Measuring, Monitoring, and Regulating Teamwork for Long Duration Missions
  - Validation of a sociometric badge developed for the monitoring of team functioning





# Countermeasures - Sleep

Human Research Program

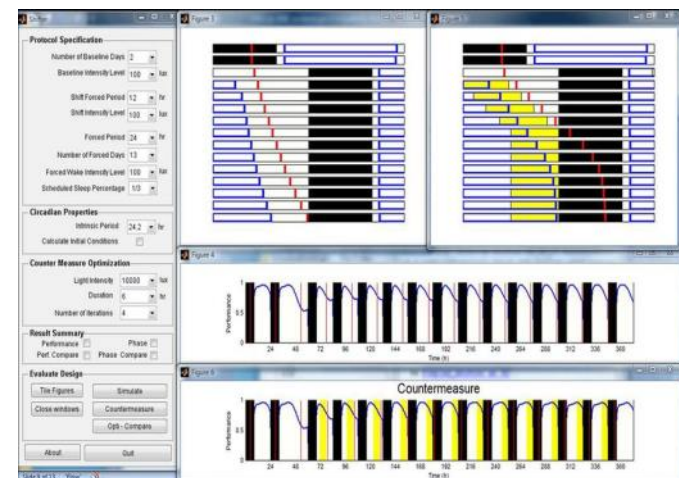
## Scheduling Tools

- ISS Program and Mission Planners have requested flight surgeon inputs into real-time scheduling decisions – currently, manual relay of information
- NASA BHP and the NSBRI are developing software to provide predictions of performance based on sleep-wake data
  - **Circadian Neurobehavioral Performance and Alertness (CNPA) (Elizabeth Klerman, Harvard Medical School)**
  - **Individualized Fatigue Meter in BHP-DS (Daniel Mollicone, Pulsar Informatics)**
- NSBRI funding integration and user-interface of models so that NASA personnel can use them as needed without relying on external experts

## -> Individualized Countermeasure Regimen

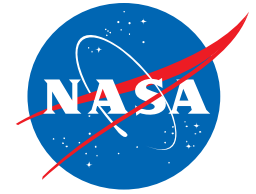
Proper scheduling of countermeasures (light, darkness, melatonin, diet, exercise, and medications) is the cornerstone for facilitating adaptation

**Future Efforts: incorporate workload**





# Behavioral Health and Performance Countermeasure plan



*Human Research Program*

- Maximize use of ground-based analogs for development
- Ultimate validation on ISS

<u>Measure/ Countermeasure Name</u>	<u>Analog Tested In</u>	<u>Anticipated Ready Date for ISS</u>
Reaction Self-Test	n/a	Currently In Flight
Cognition (Basner)	HERA	Planned Flight Study FY15
AD ASTRA	HERA, FARU, HiSEAS	FY 16
Team Performance Task	HERA, Antarctic	FY 16
BHP Dashboard	HERA	FY 16
SmartOP	MCC	FY 16
Actigraphy/EEG (SBIR Phase III)	TBD	FY 16
Communication Delay Procedures	HERA	FY 16 (if comm. delay)
Sociometric Badge	HERA, HiSEAS	FY 17
Baseline Standardized BMed Measures	HERA, Antarctic	FY 18
Neurobehavioral Conditions List	HERA, Antarctic	FY 18
Integrated Testing of Measures	HERA	FY 19
Team Mental Model Monitoring Tool (SBIR Phase III)	TBD	FY 19
Sensory Stimulation Augmentation Tools	HERA, Antarctic, Long-Duration Chamber	FY 19
Integrated Testing of Countermeasures	HERA	FY 20
VR Technologies for Behavioral Health	HERA	FY 21



# NASA ISS Astronaut LPs to Date

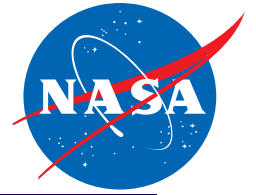


- LPs are done in crewmembers if clinically indicated
- 5 LPs conducted postflight in crewmembers with optic disc edema, no preflight LP as baseline
- Postflight LP measurements have demonstrated mild - moderate elevation in ICP, an inadequate surrogate to in-flight measurement of ICP (cephalad fluid shift & CO<sub>2</sub> challenge removed)

Case	Opening pressure (cm H <sub>2</sub> O) Normal range 10-20 cm H <sub>2</sub> O	Opening pressure (mmHg) Normal range 5-15 cm H <sub>2</sub> O	Time after flight (days)
A	22	16.2	66
B	21	15.4	19
C	28	20.6	12
D	28.5	21.0	57
E	18	13.2	8



# Ocular Health

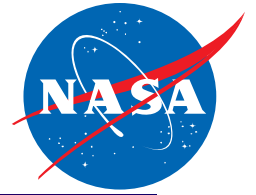


*Human Research Program*

- Occupational exposure study:
  - Define changes in crew due to ISS environment, occurring in:
    - Ocular
    - CNS
    - Cardiovascular
- Mechanistic only by observation & measurement
- Limited physiologic manipulation in comparison to FS
  - TCD measurement during tilt testing pre/post

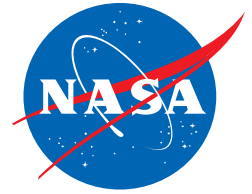


# Fluid Shifts



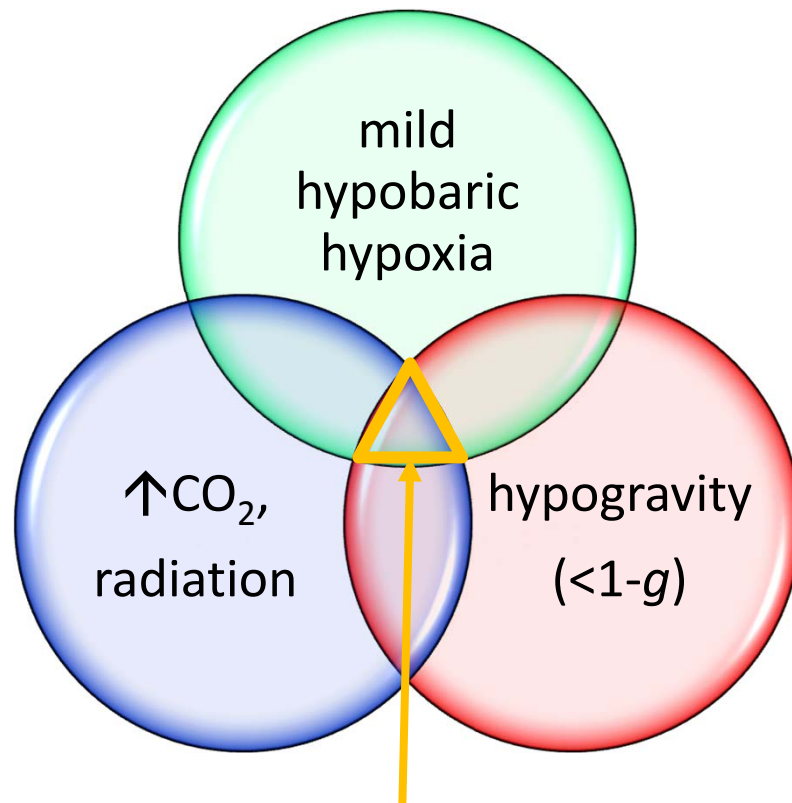
*Human Research Program*

- Mechanistic study
  - Direct manipulation of volume and fluid shift using tilt and LBNP with simultaneous measurement of changes in following systems:
    - Ocular
    - CNS
    - Cardiovascular
  - Assessment of Compartmental Fluid Shift



# Exploration Atmosphere Concerns

Human Research Program



## Health Concern:

Synergistic or additive effects of 8/32 and the expected spaceflight environment, including weightlessness, elevated CO<sub>2</sub>, radiation.

- 8/32 hypoxia not a concern for astronauts at 1-g, but due to lack of evidence is considered unacceptable today for long-duration (>1 week) exposure in space
- Significant improvement is expected at 8.2 psia, 34% O<sub>2</sub> but must be proven
- 8.2/34 to be selectively applied where it improves the overall risk posture for crew health and performance, e.g., missions with frequent EVA excursions
- No showstopper anticipated, but forward work required to validate new capability
- Physiological concerns include vision changes, sleep quality changes, increased fatigue, exercise prescription changes, acute mountain sickness, sensorimotor and immune dysfunction



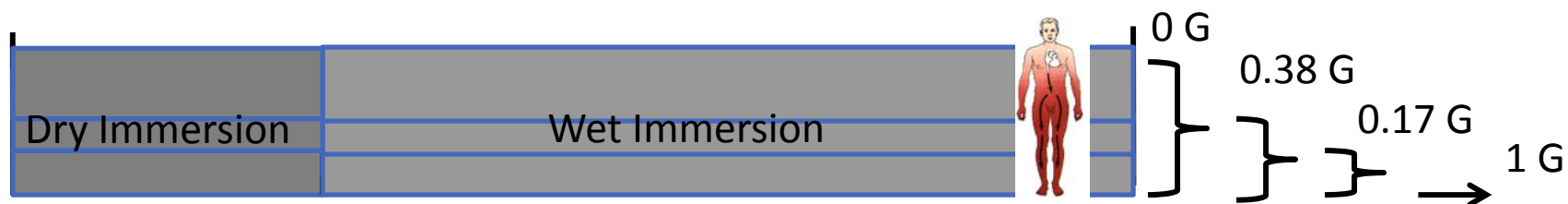


***A Vision:***

## Hypogravity Analog Model (HAM)

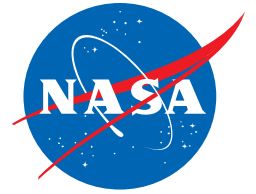
**Resting Habitat**

**Ambulatory Activities**





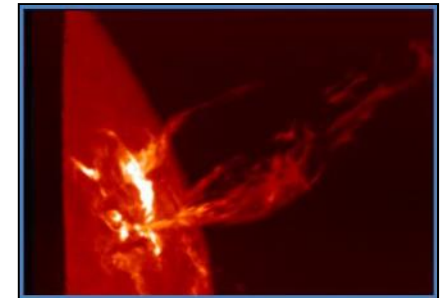
# Space Radiation Environment



Human Research Program

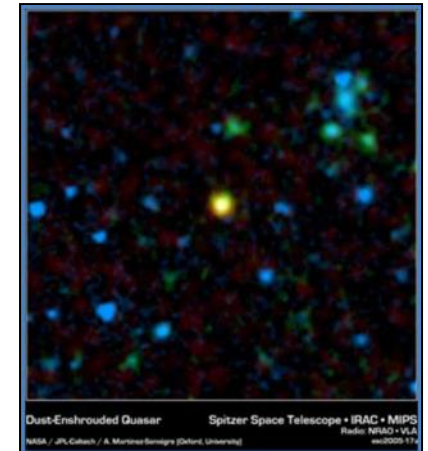
## Solar Particle Events (SPE)

- Low to medium energy protons associated with coronal mass ejection
- ARS possible from unshielded exposure to large SPE
- Effectively shielded but optimization required to reduce weight
- Main Issue: Develop accurate forecasting and dosimetry



## Galactic Cosmic Rays (GCR)

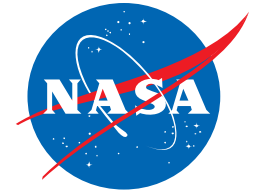
- Highly charged, energetic atomic nuclei (HZE particles) and protons
- Not effectively shielded (fragment into lighter, penetrating species)
- Abundances and energies in space environment understood
- Main Problem: uncertainty about biological effects limits ability to accurately evaluate risks and countermeasures



## Trapped Radiation (Van Allen Belts)

- Low to Medium energy protons and electrons
- Effectively mitigated by shielding
- Mainly relevant to ISS
- Main Issue: develop accurate dynamic model

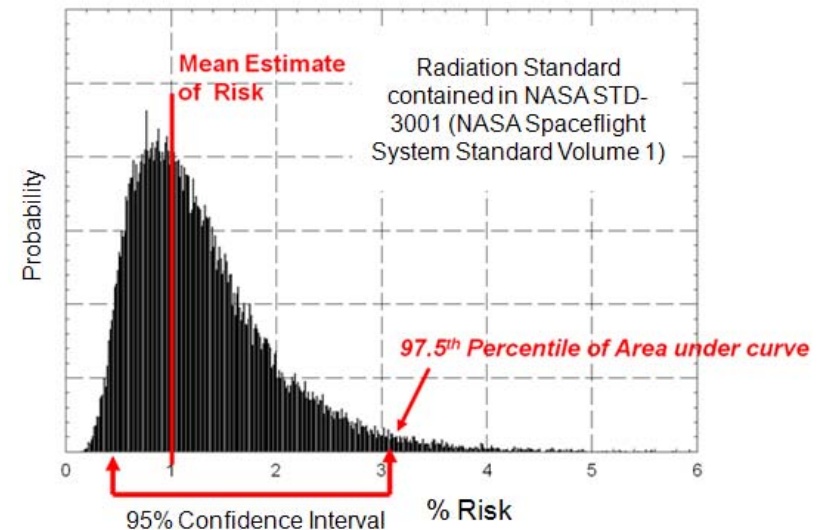




# NASA Permissible Exposure Limits

Human Research Program

- NASA-STD-3001, Volume 1 is 95% Confidence level for Risk of Exposure Induced Death (REID) less than 3%.
  - Less than 1 in 33 chance of early death
  - Best estimate is 20-years average life loss for space radiation attributable cancer
- Limit of 3% fatal cancer risk based on 1989 comparison of risks in “less-safe” industries
  - Prevent clinically significant health effects including performance degradation, sickness, or death in-flight
- Lifetime limits for lens, circulatory system, and central nervous system are imposed to limit or prevent risks of degenerative tissue diseases



## NASA-STD-3001, Volume 1, Appendix F

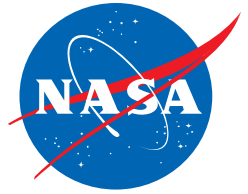
Table 4—Dose limits for short-term or career non-cancer effects (in mGy-Eq. or mGy)  
Note RBE's for specific risks are distinct as described below.

Organ	30 day limit	1 Year Limit	Career
Lens*	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500	3000	4000
BFO	250	500	Not applicable
Heart**	250	500	1000
CNS***	500	1000	1500
CNS*** (Z≥10)	-	100 mGy	250 mGy

\*Lens limits are intended to prevent early (< 5 yr) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (> 5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.

\*\*Heart doses calculated as average over heart muscle and adjacent arteries.

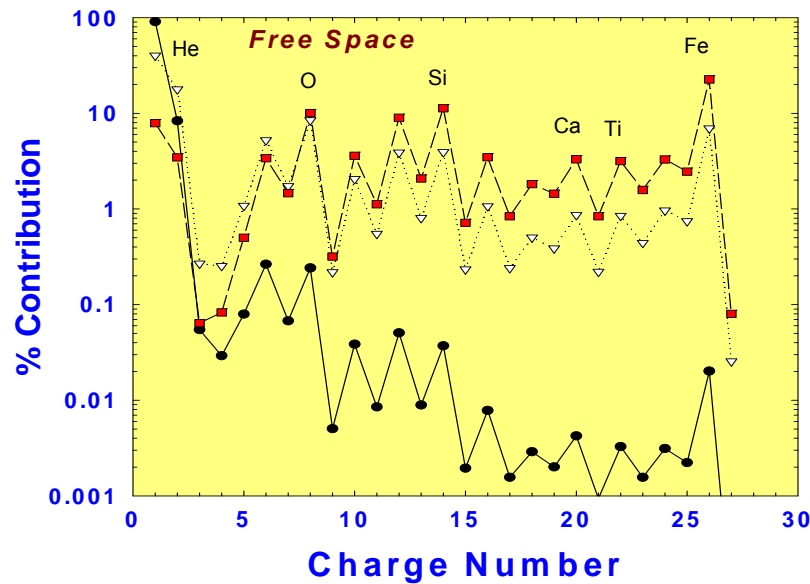
\*\*\*CNS limits should be calculated at the hippocampus.



# Galactic Cosmic Ray Contributions to Dose Equivalent

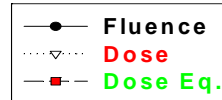
Human Research Program

## GCR Charge Contributions



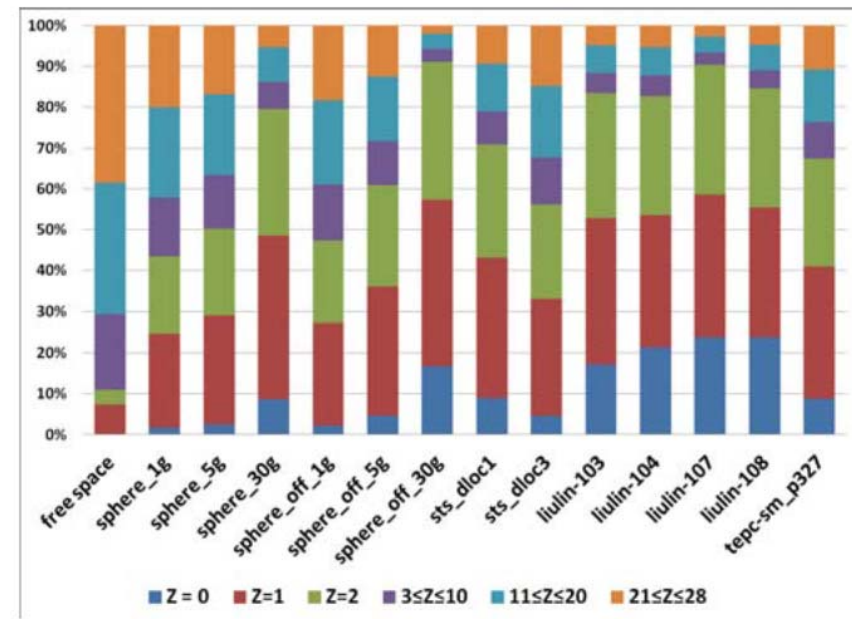
$$D = F \times \text{LET}$$

$$D.Eq = Q \times D$$



*Shielded GCR charge contributions to dose equivalent*

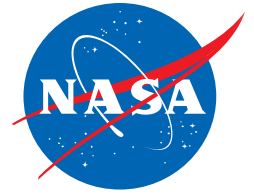
*GCR Contributions to dose equivalent at 5 g/cm<sup>2</sup> (Cucinotta et. al. 2003)*



Percent contribution to BFO dose equivalent by charge group.



# Examples of Current Modeling Efforts



*Human Research Program*

<http://three.usra.edu/#section=encyclopedia>

## **Acute Radiation Risk and BRYNTRN Organ Dose (ARRBOD) Projection**

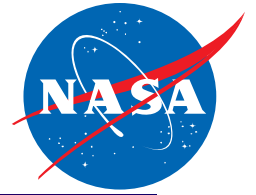
The NASA Baryon Transport code (BRYNTRN) and the Acute Radiation Risk (ARR) code have been combined into a user friendly Graphical User Interface (GUI) to predict organ doses and prodromal risks for major solar particle events. The ARRBOD GUI is intended for mission planners, radiation shield designers, space operations in the mission, and space biophysics researchers. The ARRBOD GUI will serve as a proof-of-concept example for future integration of other human space applications risk projection models.

**Lung Cancer Explorer** - The Lung Cancer Explorer, an open web portal to explore gene expression and clinical associations in lung cancer, was developed at The University of Texas Southwestern Medical Center (partially supported by the NASA funded UT Southwestern Medical Center Lung Cancer NSCOR grant, NNX11AC54G). This database aggregates over 30 public clinically-annotated lung cancer gene expression studies, along with some private data from the University of Texas Southwestern Medical Center, and presents a user-friendly, web-based interface to explore and analyze this data.

**GCR Event-Based Risk Model (GERMcode):** GERMcode allows scientists to model beam line experiments, such as those performed at the NASA Space Radiation Laboratory, utilizing variables for ion type, shielding materials, and sample holders. The software enables experimenters to interpret their data and to estimate the basic physical and biological output of the experiments. The software allows simulation of heavy ion beams including energy loss (LET), nuclear interactions, track structures, and Bragg curves and to integrate biological response models with physical descriptions of heavy ion beams.



# Examples of Current Modeling Efforts



*Human Research Program*

**HZETRN2010:** allows research scientists and engineers the ability to propagate solar particle event (SPE), galactic cosmic ray (GCR), or user-defined environments through bulk shielding materials and compute particle fluence spectra, dose, dose equivalent, and linear energy transfer (LET) spectra.

**NASA Space Cancer Risk Integrated Tools:** A cancer risk projection code including evaluation of the level of uncertainty that exists for each of the factors (parameters) that are used in the model. The model originated from recommendations of the National Council on Radiation Protection and Measurements (NCRP, 1997; 2000) with revisions from the latest analysis of human radio-epidemiology data. NASA-defined radiation quality factors are formulated with probability distribution functions (PDFs) to represent uncertainties in leukemia and solid cancer risk estimates.

**OLTARIS:** The On-Line Tool for the Assessment of Radiation in Space is a web-based set of tools and models that allows engineers and scientists to assess the effects of space radiation on spacecraft, habitats, rovers, and spacesuits.

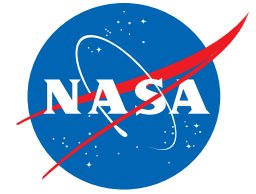
**Relativistic Ion Tracks:** RITRACKS simulates the stochastic nature of the energy deposition of relativistic ions. It was developed to use the Monte Carlo technique to simulate a stochastic cascade of biological events. RITRACKS illustrates the biophysical model of ionization and the excitation processes of the ion's track and the electrons liberated by the ion.

**System Biology-based cancer models:** The main model we have developed within this NSCOR is an agent-based model (ABM) of the mammary gland consisting of a hierarchy of mammary stem, progenitor, and differentiated cells.





# Example of NASA Space Radiation Lab Energy Beams and Characteristics



Human Research Program

Beam*	Energy, MeV/n	LET, keV/μm	Range in Water, cm
protons	50-2500	1.2 - 0.20	2 to >100
<sup>4</sup> He	50- 1000	5 – 0.9	2 to >100
<sup>16</sup> O	50- 1000	80 – 14	0.5 – 80
<sup>20</sup> Ne	70-1000	96 – 22	0.45 – 65
<sup>28</sup> Si	93-1000	151 – 44	0.66 – 46
<sup>35</sup> Cl	500-1000	80 – 64	14 – 40
<sup>48</sup> Ti	150-1000	265-108	1.5 – 32
<sup>56</sup> Fe	50-1000	832 – 150	0.2 – 27
Sequential Field (H/Fe)	1000	0.2/150	See above
Tandem Low Energy Beams	E<7 MeV/n for B, C, Si, and Fe ions	Various	Various

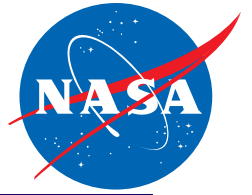


Before final award of selected proposals, the SRPE will further review the choices of beams and doses to be used in funded research plans.





# Description of SHFH Data and Limitations

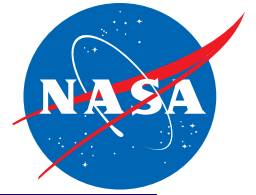


*Human Research Program*

- Space Flight Data Examples – Most of the human factors data are anecdotal, such as post-flight crew comments
  - Limited anthropometric measurements such as seating height changes and body volume based on manual measurements and photographic analysis
  - Limited task performance data (task completion and error)
  - Inflight questionnaires
- Current ISS information is mostly from post-flight Crew Debriefs
- We are capturing additional types of human performance metrics and spaceflight evidence
  - What data do we already have that may help close our research gaps?
    - Data mining of operational data from Shuttle and ISS, as well as DoD
  - How do we systematically collect new data?
    - Development of standard performance metrics and tools for data collection in both ISS and analog environments



# SHFH Countermeasures Development

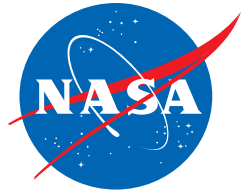


Human Research Program

- Certain research areas require *true* microgravity environment for data acquisition and countermeasure development
  - 3-D space utilization and its impact on net habitable volume
  - Changes in spinal growth and its effect on suit design and sizing
- Use ground-based studies for the areas that do not necessarily require microgravity
  - Human-robot Interaction
  - Human-automation interface
  - Human-computer interaction
- Validate countermeasures on ISS

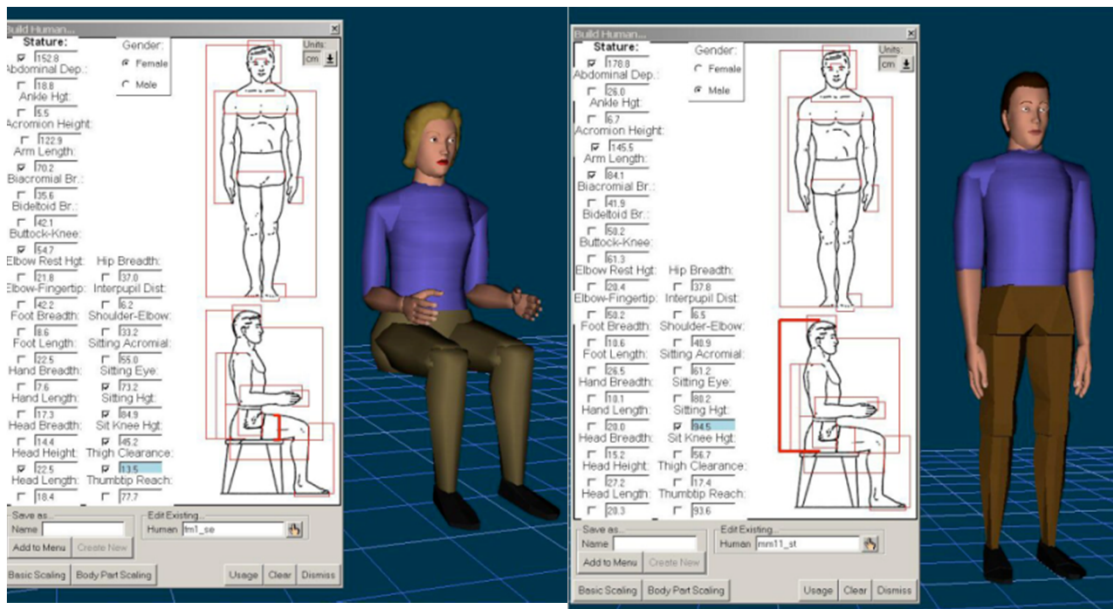


# Past and Current Human Modeling Efforts in Human Factors

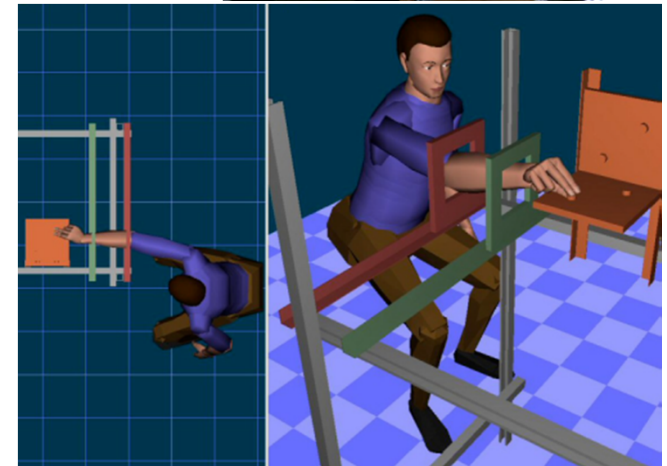


Human Research Program

- Human Modeling in System Design
- Human Performance Modeling



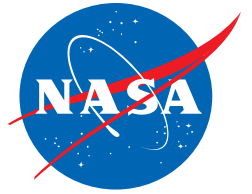
Static Human Models



Simulation-based Tests of Reach and Access

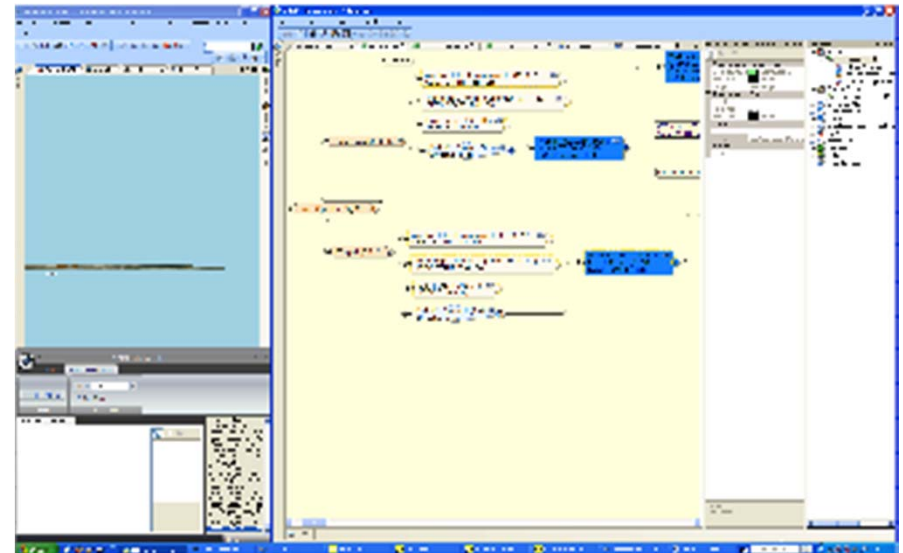


# Man-machine Integration Design and Analysis System (MIDAS)



Human Research Program

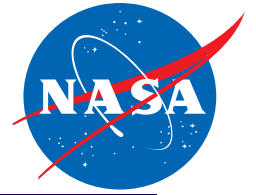
- ✓ Validated, first-principle models of human behavior including perception, visual attention, memory, & workload
- ✓ 3D CAD models of the environment, the workstation, and the equipment
- ✓ Controls a generic, anthropometrically-correct human mannequin (Jack™, 5th percentile female - 95th percentile male)
- ✓ Monte carlo simulation capability with stochastic human performance



- ✓ Distributed simulation (e.g. Microsaint Sharp)
- ✓ Generates realistic task-management behaviors sensitive to task context, environment
- ✓ Produces task timelines, workload, and situation awareness profiles and visualization which permits testing of procedure alternatives



# Computational Model for Spacecraft/Habitat Volume (New Project)



Human Research Program

- A key design challenge for future long-duration exploration missions is determining the appropriate volume of a spacecraft/habitat to accommodate habitability functions and ensure optimal crew health, performance and safety.
- Because spacecraft/habitat volume directly drives mass and cost, this information is needed early in the design process.

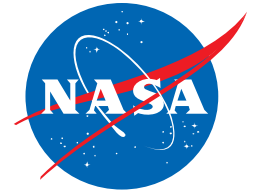


@AstroRM: "In my crew quarters on station. 3'x3'x6.3' I barely fit but it is home. I have my sleeping bag and computer and pics"

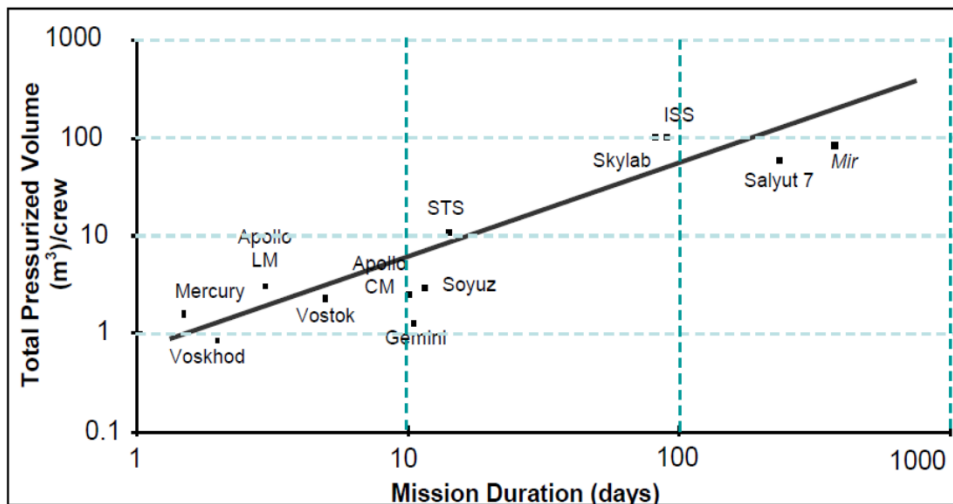




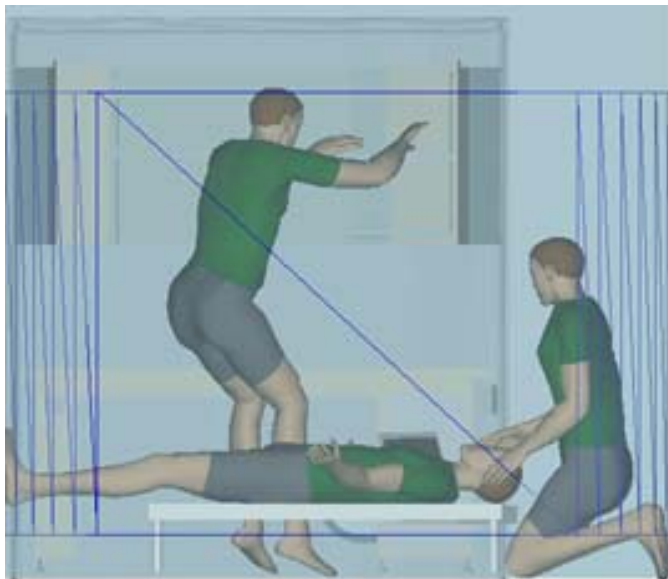
# Computational Model for Spacecraft/Habitat Volume (Continued)



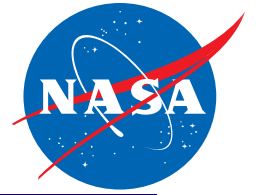
Human Research Program



- Existing guidelines draw from interpolations and extrapolations based on volumes of historical spacecraft and habitats, or they simply provide required volume for specific tasks.



- A “bottoms-up” method based on mission attributes and critical task volumes represents an approach better aligned with a human-centered design philosophy.



# IMM Evidence Base

*Human Research Program*

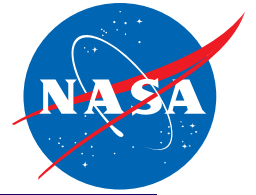
- Lifetime Surveillance of Astronaut Health
- ISS Expeditions 1 thru 13 (2006)\*
- STS-01 thru STS-114 (2005)
- Apollo, Skylab, Mir (U.S. crew only)
- Review of crew medical charts
- Analog, terrestrial data
- Bayesian Analyses
- Independent Predictive Models
- Flight Surgeon Delphi Study
- **Russian medical data not used**

\* More current data used for Visual Impairment Intracranial Pressure (VIIP)





# Countermeasure Identification

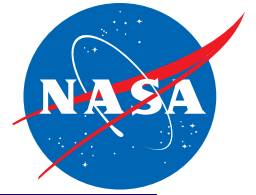


*Human Research Program*

- Use of evidence-based tools, primarily the Integrated Medical Model (IMM), to help quantify risk contributors with other analytic techniques being employed where appropriate.
- Conditions contributing to medical risk are identified and quantified:
  - Integrated Medical Model
  - Exploration Medical Condition List
  - Subject Matter Experts
- Information can be communicated to mission architecture teams with the goal of minimizing medical risk



# Additional Brainstorming

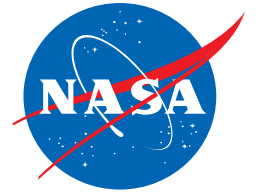


*Human Research Program*

- Various medical conditions are under investigation by other Elements
  - Review their investigation plan. Does it include plans for prevention, diagnosing, etc.
  - Analyze data from other Elements to determine if additional cause/effect relationships exists regarding medical conditions under the purview of ExMC



# Computational Model for Spacecraft/Habitat Volume Study Objectives and Approach

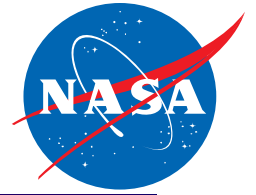


*Human Research Program*

- A computational model based on mission tasks will:
  - Support iterative design process
  - Reduce design and mission risks
  - Improve spacecraft volume design and operations
- Specific Aims:
  - Generate a set of optimal spacecraft/habitat volumes for a given mission.
  - Generate associated layout assumptions that will provide an early indication of the spatial characterizations of a given space.
  - Perform assessments of the viability and acceptability of the volumes based on outputs from the model, described via a set of performance metrics.
  - Perform assessments to provide a characterization of risks across the model parameter space.



# Summary



*Human Research Program*

- Summarize spaceflight effects, risks for future missions
- Summarize current countermeasures and why we're interested in methods to identify countermeasure targets with cross-disciplinary benefits (e.g. minimize resource utilization)
- Summarize research venue opportunities (to keep in mind for brainstorming future collaborative work)
- Summarize current modeling efforts and why we're interested in additional techniques to enable integration and system-level behavior insights
- Summarize data descriptions (also to keep in mind for brainstorming future collaborative work)